Evaluation of Errors Associated with Bowen Ratio Energy Balance Method in Estimating Sensible and Latent Heat Fluxes Over Grass in Akure, Nigeria

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Abstract: ***One of the standard techniques used to measure evapotranspiration indirectly is Bowen ratio-energy balance (BREB) method. It is a micrometeorological technique, and it is widely used because of its simplicity, robustness, and affordability. This method has been applied in this study to partition available energy (R_n – G) into turbulent fluxes at the study site during wet and dry periods (July to December, 2014).BREB method estimates sensible and latent heat fluxes from measures of vertical gradients of air temperature and vapour pressure. Both net radiation and soil heat flux are measured directly. These are then combined in surface energy balance equation.Results show that apart from errors of measurement of net radiation and soil heat flux introduced into the estimates of turbulent fluxes, Bowen ratio-energy balance method often produces totally unacceptable results. Wrong signs, and extremely inaccurate magnitude of latent and sensible heat fluxes which occurs when Bowen ratio approaches -1 are common with this method. These problems occur as a result of resolution limits of instruments used.Also, under moist conditions, the BREB method can give good results for evapotranspiration estimates, but the method may not be so accurate under very dry conditions. Under moist conditions, error analysis showed that relative error in evapotranspiration is only small if the relative error in Bowen ratio is also small. In dry conditions, however, the absolute error in evapotranspiration is always fairly small because of the small value of evapotranspiration itself.In this study, errors associated with Bowen ratio-energy balance method are evaluated. A method to find the range of Bowen ratio around -1 which produces inaccurate flux estimates of latent and sensible heat fluxes is presented. The excluded region of Bowen ratio is not constant but depends on the vapour pressure differences measured in each averaging period and the resolution limits of the device used. If temperature and vapour pressure gradients and the resolution limits of the sensors are known, spurious data obtained from the BREB method would easily be recognized. Objective criteria to eliminate spurious data are also presented.***

Keywords: Bowen ratio, Energy balance, Turbulent heat fluxes, Vapour pressure gradient, Error analysis

1. Introduction

Evapotranspiration is a component of the hydrological cycle whose calculation at the local and regional scale is needed to achieve an appropriate management of water requirements. A high degree of precision in estimating crop evapotranspiration may permit important water savings in the planning and management of irrigated areas. The partitioning between latent LE and sensible H heat fluxes, that is the Bowen ratio β = H/LE, is critical in determining the hydrological cycle, boundary layer development, weather and climate. β can be interpreted as an indicator of water stress (Perez et al., 2008).

The BREB method estimates turbulent fluxes of latent and sensible heat from measures of the vertical gradients of air temperature and vapour pressure, along with direct measures of net radiation and the soil heat flux (Fritschen and Simpson, 1989). It is an indirect method, compared to methods such as eddy covariance, which directly measures turbulent fluxes, or weighing lysimeters, which measure the mass change of an isolated soil volume and plant growing in it. Its advantages include straight-forward, simple measurements; it requires no information about the aerodynamic characteristics of the surface of interest; it can integrate latent heat fluxes over large areas (hundreds to thousands of square meters); it can estimate fluxes on fine time scales (less than an hour); and it can provide continuous, unattended measurements (Todd et al., 2000).

The BREB method does have a number of well documented limitations. The first of these lies in the sensors' ability to accurately measure the non-turbulent energy terms, or the available energy (Rn – G). Errors in the measurements of Rn and G are propagated into the estimates of the turbulent fluxes (Ohmura 1982). Also, when β approaches -1, or when Rn – G approaches zero (often during sunrise and sunset), the BREB technique becomes computationally unstable and the results have no physical meaning (Prueger et al. 1997). Finally, there are periods when this method can yield apparently counter-gradient fluxes (Perez et al. 1999).

To avoid the uncertainty of the BREB method that mostly occurs when the Bowen ratio (β = sensible heat (H)/Latent heat (LE)) approaches -1, certain number of observations obtained under these conditions must be treated as bad data and discarded during data analysis. Unland et al. (1996) have recommended the exclusion of two levels data when $|\Delta e| < 0.005$ kPa and $\beta \approx -1$, particularly for range between $|1 + \beta| < 0.3$. In such case, the values of LE and H must be obtained as the average of the values obtained before and after the considered time interval. For the cases in which the β values are close to −1, some authors eliminate β values lower than −0.75, or values in the range $-1.3 < \beta < -0.7$ (Ortega-Farias et al., 1996; Unland et al., 1996). But that interval should depend on the measurement accuracy of the sensors used.

This study aims at determining the occurrence of errors associated with the BREB method by judging it with the criteria already developed for rejecting spurious Bowen ratio data (Ohmura, 1982; Perez et al.,1999; Unland et al.,1996; Ortega-Farias et al., 1996). This would yield the same result as comparing BREB method with a more reliable technique for measuring evapotranspiration like eddy covariance method, lysimetric method or bulk aerodynamic method. This study also develops objective criteria to accept/reject data for the BREB flux estimates at the tropical humid regions for agricultural, hydrological and climatological use.

2. Data and Method

2.1 Experimental site

The study site is located at Federal University of Technology Akure, with geographical coordinate 7.25710N, 5.20580E. By climatological classification, Akure is situated within the tropical wet and dry belt of West Africa (Griffiths, 1974). The seasonal pattern is monsoonal, with alternating periods of wet (March/April – October) and dry (November – February) months. The weather change is as a result of the meridional movement of Inter-Tropical Discontinuity (ITD) line, which demarcates at the surface the warm and moist (maritime) south-westerly flow from the hot and dry (continental) north-easterly winds (Oladosu et al., 2007). The annual average rainfall amount is 1281mm and the annual average temperature is 27.3^{0}C with weak surface wind flow of less than 1.5m/s, which is generally a prominent feature of the tropical area.

2.2 Instrumentation used

A micrometeorology tower was mounted over carpet grass (Axonopus fissifolius) on which net radiometer (NR-Lite2) and pyranometer (CS 300) were installed at about 1m while the windsonic (ultrasonic wind sensor) was installed at 2m above the grass. Also in the tower, temperature and relative humidity probes (HC2S3) were installed at two levels (0.5m and 2m) above the grass. Two soil heat flux plates (HFP01) were buried at 0.1m beneath the soil under the grass and four soil thermocouples (TCAV, CSI), two of which were buried above each plate at 0.02m and 0.06m. All these sensors were connected to a data acquisition system (Data logger 100X of Campbell Scientific Inc.) programmed for collecting data every second and storing the averages every 10minutes, from which mean hourly values were obtained.

2.3Bowen ratio energy balance

This method is based on the theory that one-dimensional fluxes of sensible and latent heat can be described in terms of flux-gradient relationships (Tanner 1988);

$$H = \rho C_p K_h \left(\frac{\Delta T}{\Delta z}\right) \quad (2.1)$$

$$LE = \left(\frac{\lambda\rho\varepsilon K_w}{P}\right)\left(\frac{\Delta e}{\Delta z}\right) \quad (2.2)$$

Bowen (1926) expressed the Bowen (β) as;

$$\beta = \frac{H}{LE} \quad (2.3)$$

Substituting equations (2.1) and (2.2) into equation (2.3), and assuming K_h = K_w (Verma et al., 1978; Cellier and Brunet, 1992), β can be obtained from the (Bowen, 1926):

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \quad (2.4)$$

The one-dimensional surface energy balance equation is given as follows:

$$R_n - G = H + LE \quad (2.5)$$

From equations (2.3) and (2.5), LE is given as;

$$LE = \frac{(R_n - G)}{(1+\beta)} \quad (2.6)$$

and the sensible heat is given as

$$H = \beta\frac{(R_n - G)}{(1+\beta)} \quad (2.7)$$

where H, LE, R_n and G are sensible, and latent heat fluxes, net radiation and soil heat flux respectively. All of them are measured in Wm^{-2}, ρ is air density (Kgm^{-3}), C_p is the specific heat of air at constant pressure (JKg^{-1} ^{0}C^{-1}), T is the air temperature (^{0}C), z is the height of measurement (m), λ is the latent heat of vapourization (JKg^{-1}), ε is the ratio of the molecular weight of water to that of dry air (0.622), P is the atmospheric pressure (KPa), K_h and K_w are the eddy diffusivities of heat and water vapour respectively (m^{2}s^{-1}), $\gamma = \frac{C_p P}{\varepsilon\lambda}$ is the psychrometric constant (KPa^{0}C^{-1}). ΔT and Δe are obtained by measuring air temperature and vapour pressure at two heights above the top of the grass, within the boundary layer.

Since latent heat depends on temperature, the latent heat of vapourization was computed from the relation;

$$\lambda = l_{v0} + (C_{pv} - C_{pw})(T - T_0) \quad (2.8)$$

where l_{v0} is the specific latent heat of vaporization at the reference temperature T_0. For the reference temperature T_0 = 0^{0}C with l_{v0} = 2.5*10^6 JKg^{-1}, C_{pv} =1850 JKg^{-1}K^{-1}, and C_{pw} =4218 JKg^{-1}K^{-1}.

The soil heat flux G was obtained as follows;

$$G = HF + \Delta S \quad (2.9)$$

where HF is the soil heat flux measurement from the soil heat flux plate, and ΔS is the change in heat storage above the soil heat flux plate, estimated from the following equation;

$$\Delta S = (\rho_s C_s + \theta\rho_w C_w)\frac{d\bar{T}}{dt}\Delta z \quad (2.10)$$

where ρ_s is the soil bulk density, in kg of dry soil per cubic meter (kgm^{-3}), C_s is the specific heat of dry soil (Jkg^{-10}C^{-1}), θ is the volumetric soil water content, in volume of water per unit volume of soil, dimensionless. ρ_w is the density of water (kgm^{-3}), C_w is the specific heat of water (Jkg^{-10}C^{-1}), $\bar{T}$ is the depth-average temperature of the soil layer (^{0}C), t is the time in seconds, Δz is the depth of soil heat flux pate (m).

2.4 Criteria for Rejecting Erroneous Data from the BREB Method

2.4.1 Fluxes with wrong signs

The sensible and latent heat fluxes estimates obtained from the BREB method should be in accordance with the flux-gradient relationships. Sometimes the measurements give wrong signs for the fluxes. Ohmura (1982) indicated that valid data should meet the following inequalities;

$$\text{If } R_n - G > 0 \text{ then } \Delta e + \gamma\Delta T > 0 \text{ or } \Delta T > \frac{-\Delta e}{\gamma}$$

$$\text{If } R_n - G < 0 \text{ then } \Delta e + \gamma\Delta T < 0 \text{ or } \Delta T < \frac{-\Delta e}{\gamma} \quad (2.11)$$

2.4.2Extremely inaccurate fluxes

When Bowen ratio approaches -1, even though it may not be -1 precisely, the LE flux calculated becomes unreasonable. To address this problem, Ohmura (1982) suggested that β approaches -1 only when the temperature gradient falls within the range defined by the inequality represented by (2.12).

$$D < \Delta T < F \qquad (2.12)$$

where $D = -\left(\frac{\Delta e}{\gamma}\right) - 2\left[\left(\frac{\delta\Delta e}{\gamma}\right) + \delta\Delta T\right]$ and

$F = -\left(\frac{\Delta e}{\gamma}\right) + 2\left[\left(\frac{\delta\Delta e}{\gamma}\right) + \delta\Delta T\right]$

δΔe and δΔT are the resolution limits of the vapour pressure and temperature respectively

2.4.3Boundaries on Bowen ratio around -1

In addition to the criterion mentioned in (2.12), since the estimates of LE lose their numerical meaning, the prohibited range around -1 needs to be considered. A common rejection procedure involves rejecting data for which -1.25 < β < -0.75 (Tanner et al., 1987) or using similar limits (for example Ortega-Farias et al., 1996; Brotzge and Crawford 2003). The range should however depend on the accuracy of measurement that is on the sensors used for measurement (Perez et al., 1999).

The excluded interval of β values is given as;

$-1-|\varepsilon| < \beta < -1+|\varepsilon|$

$$\text{where } \varepsilon = \frac{\delta\Delta e - \gamma\delta\Delta T}{\Delta e} \qquad (2.13)$$

ε is the error interval of Bowen ratio values around -1. Therefore, rather than being fixed, ε depends on the vapour pressure gradient in each period and on the resolution limits of the sensors. Bowen ratio energy balance method would fail if the conditions indicated in the table (1) are not met (Perez et al., 1999).

Table 2.1: A typical table showing summary of cases when BREB method fails. Rn − G is the available energy, Δe the vapor pressure difference between the lower and the upper measurement levels, β the Bowen ratio, T and e are the air temperature and vapor pressure, and ε the error interval defining the excluded interval of Bowen ratio values around −1.

Error	Condition
1	$R_n - G > 0,\ \Delta e > 0$ and $\beta < -1 + \lvert\varepsilon\rvert$
2	$R_n - G > 0,\ \Delta e < 0$ and $\beta > -1 - \lvert\varepsilon\rvert$
3	$R_n - G < 0,\ \Delta e > 0$ and $\beta > -1 - \lvert\varepsilon\rvert$
4	$R_n - G < 0,\ \Delta e < 0$ and $\beta < -1 + \lvert\varepsilon\rvert$
5	Unsteady state (of T and e)

3. Results and Discussion

The occurrence of erroneous Bowen ratio data and their causes when using the Bowen ratio Energy Balance method for different case studies are shown in the figure 3.1 to figure 3.8.

3.1 Fluxes with wrong signs

Figure 3.1 to figure 3.8 display time series plot of the surface energy balance for July 2014. They show typical diurnal pattern of the estimated energy balance components over carpet grass (Axonopus fissifolius) during wet season.

In figure 3.1, Bowen ratio Energy Balance method failed for the hours between 0000 hours and 0700 hours and between 1600 hours and 2300 hours because sensible and latent heat flux estimates were not in accordance with the flux-gradient relationships. The measurements gave wrong signs for the fluxes. Flux-gradient relationships are such that if the gradients of temperature and vapour pressure are negative (lapse condition), sensible and latent heat fluxes should be positive and vice versa. The estimated fluxes gave flux directions which were the same as that of the gradients and this was not conformable with the flux-gradient relationships, although the magnitudes were correct. For instance, the values of the estimated latent heat fluxes were negative, indicating condensation when vapour pressure differences were positive, suggesting evapotranspiration, which were supposed to give negative fluxes. The data must therefore, be rejected outright.

Ohmura, 1982 indicated that errors in net radiation, soil heat flux and humidity and temperature profiles are the causes of this problem. It was observed in this study that temperature also caused failure of BREB method at these hours. Although temperature lapsed in the atmosphere, it was so low that saturation was quickly reached and the result was condensation but evapotranspiration was expected. The formation of dew on the net radiometer during early morning hours may also be connected with the inconsistent partitioning of the available energy at these periods. This was the reason why latent heat was greater than the available energy during early morning hours. Also, during these periods of dew deposition, differences of temperature and, or vapour pressure were very small (atmosphere was stably stratified and winds were weak). Measuring vapour pressure concentration gradients was difficult because sensor errors were often of the same order of magnitude or even larger than the gradients themselves. Consequently, the main problem was no longer absolute precision, but instead the resolution of the sensors.

Weak turbulence affected the data between 1600 hours and 2100 hours. The inversion that also occurred during those periods had further suppressed turbulent exchanges, thereby, diminishing vapour pressure concentration gradients because cold air had concentrated in the equilibrium (or fully adjusted) layer. Hence, vapour pressure differences were small for most of the periods and fell within the sensor error. The main problem was therefore, not absolute precision but the resolution limit of the sensor used. If the resolution of the sensors can be improved this problem will be reduced. The resolution limit of a sensor is the smallest change it can detect in the quantity it is measuring. Below this limit error will be propagated into the measurement. Additionally, the BREB method failed as a result of wrong signs it gave for both sensible and latent heat fluxes for those periods (fig 3.1).

Figure 3.2 shows the corrected diurnal variation of surface energy fluxes for 1st July, 2014. Bowen ratio datum for 1000 hours in figure 3.1 increased anomalously due to sharp increase in air temperature (table 3.1). Data rejection is necessary for such period. For such time-periods, Bowen ratio data were rejected and calculated as averages between the preceding and succeeding values. Such correction is shown in figure 3.2.

In figure 3.3, there was condensation around 1000 hours which made latent heat to be negative. Latent heat was released which was instantly converted to sensible heat. This was the reason why latent and sensible heat fluxes were transported in opposite direction. This also buttressed the fact that BREB method fails during condensation or precipitation as indicated by Ohmura (1982).

The conditions indicated by (eqn 2.11) were not often satisfied with the early morning and late afternoon data. Also, during precipitation, when vapour pressure differences (Δe) were very small (close to the resolution limit of the sensor), and the net radiation or soil heat flux were small or not measured accurately (Ohmura,1982; Perez et al., 1999).

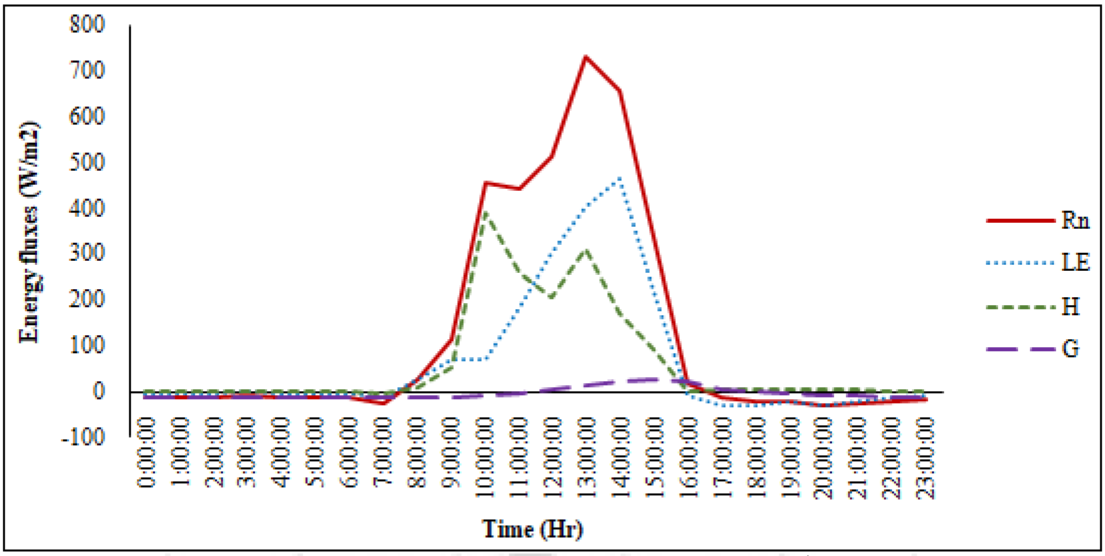

Figure 3.1: Diurnal variation of surface energy fluxes on 1st July, 2014.

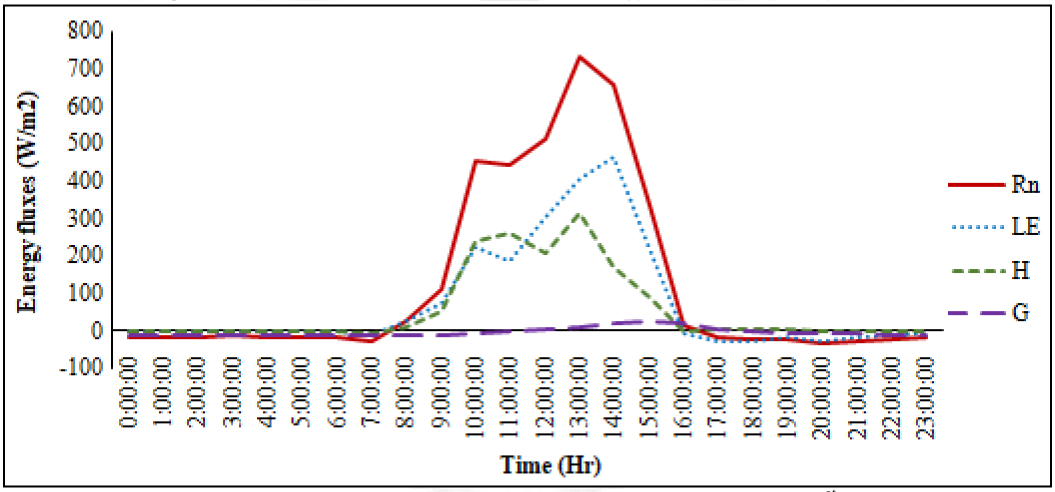

Figure 3.2: Modified diurnal variation of surface energy fluxes on 1st July, 2014.

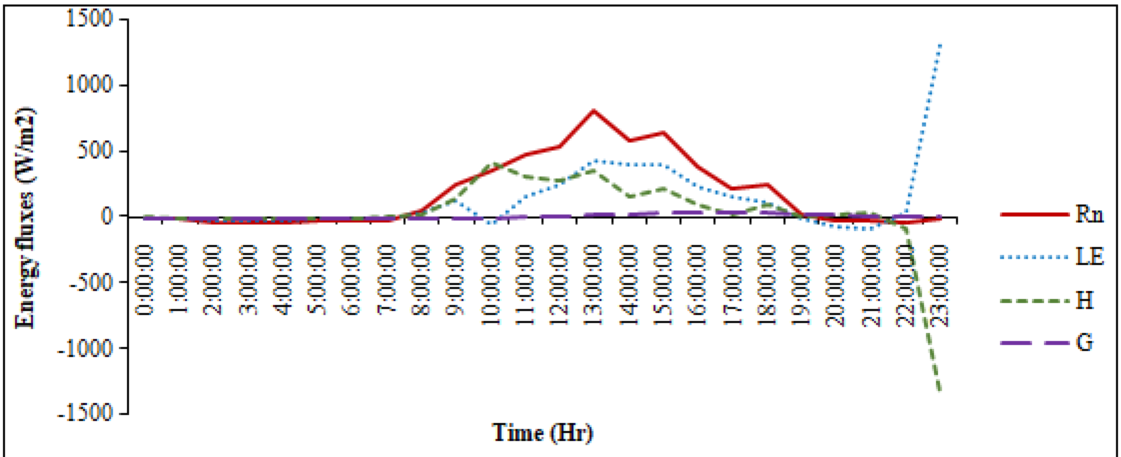

Figure 3.3: Diurnal variation of surface energy fluxes on 2nd July, 2014.

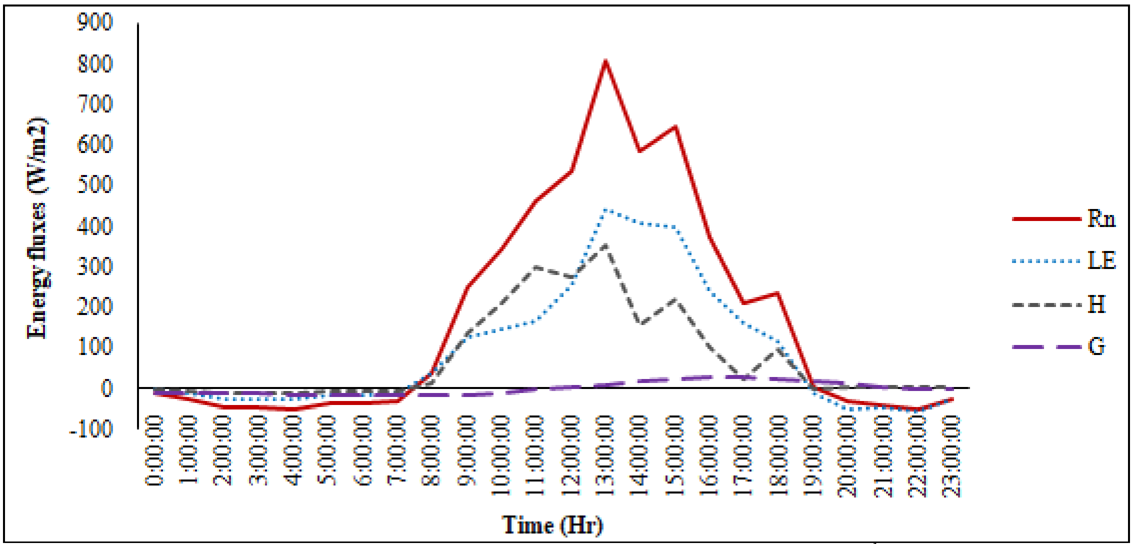

Figure 3.4: Modified diurnal variation of surface energy fluxes on 2nd July, 2014.

Table 3.1 shows estimated data obtained from BREB method for 1st July, 2014. Data for the hours between 0000 and 0700 are unacceptable because they gave wrong signs for the turbulent fluxes. Evaporation was expected since vapour pressure differences were positive, but the temperatures were too low to facilitate condensation, thus, giving negative latent heat fluxes for those periods. Even though, the temperature lapsed with height in the atmosphere, there were no significant vapour pressure gradients so that vapour pressure differences were small and close to the resolution limit of the sensor. This had even contributed to the unacceptability of the data for those times. Data for 400 hours to 700 hours show that latent heat flux estimates were greater than the available energy (Rn-G). Only inversion can cause this since energy for evapotranspiration has to be drawn from the air. Even if ΔT is continually reduced and Δe is left as it is, not most accurate Bowen ratio equipment can give reasonable partitioning of the available energy into turbulent fluxes in this condition. The exception to this was the data for 0300 which gave correct signs for the fluxes but the fact that the vapour pressure difference was small and fell within sensor error led to the rejection of the data for that period. Wind speeds were also low, (U < 1m/s), suggesting that turbulence was not well developed.

Table 3.1: A typical table showing cases of wrong signs for turbulent fluxes calculated by the Bowen ratio energy balance method for 01 July, 2014

Time	ΔT	Δe	β	LE	H	Δe/ϒ	Δe+ϒΔT	Rn-G	Remark
1:00:00	-0.002	0.012	-0.009	-2.472	0.023	-0.181	0.012	-2.450	Rejected
2:00:00	0.013	0.008	0.104	-2.002	-0.208	-0.128	0.009	-2.210	Rejected
3:00:00	0.037	0.007	0.354	0.220	0.078	-0.104	0.009	0.297	Rejected
4:00:00	0.032	0.005	0.379	-1.546	-0.585	-0.084	0.007	-2.131	Rejected
5:00:00	0.042	0.007	0.380	-3.393	-1.289	-0.110	0.010	-4.682	Rejected
6:00:00	0.058	0.010	0.381	-0.788	-0.300	-0.153	0.014	-1.088	Rejected
7:00:00	0.028	0.005	0.384	-11.788	-4.531	-0.074	0.007	-16.318	Rejected
8:00:00	0.125	0.021	0.379	27.570	10.435	-0.330	0.029	38.005	Accepted
9:00:00	0.267	0.024	0.724	72.033	52.126	-0.369	0.041	124.159	Accepted
10:00:00	1.502	0.018	5.408	72.357	391.290	-0.278	0.114	463.647	Rejected
11:00:00	1.665	0.076	1.413	184.785	261.046	-1.179	0.183	445.831	Accepted
12:00:00	1.100	0.104	0.679	302.760	205.442	-1.621	0.175	508.202	Accepted
13:00:00	1.082	0.090	0.772	406.316	313.674	-1.401	0.159	719.991	Accepted
14:00:00	0.913	0.161	0.363	466.423	169.330	-2.516	0.220	635.753	Accepted
15:00:00	0.423	0.066	0.410	221.195	90.644	-1.033	0.093	311.839	Accepted
16:00:00	-0.163	0.071	-0.147	-8.218	1.210	-1.110	0.061	-7.008	Rejected
17:00:00	-0.117	0.041	-0.183	-27.263	4.997	-0.637	0.033	-22.266	Rejected
18:00:00	-0.100	0.029	-0.224	-28.646	6.411	-0.447	0.022	-22.235	Rejected
19:00:00	-0.057	0.020	-0.179	-19.894	3.551	-0.318	0.017	-16.343	Rejected
20:00:00	-0.025	0.017	-0.093	-26.756	2.490	-0.269	0.016	-24.265	Rejected
21:00:00	-0.023	0.009	-0.169	-20.070	3.399	-0.138	0.007	-16.671	Rejected
22:00:00	0.012	0.006	0.117	-10.239	-1.199	-0.100	0.007	-11.437	Rejected
23:00:00	0.030	0.007	0.290	-4.886	-1.416	-0.104	0.009	-6.302	Rejected

3.2 Extremely inaccurate magnitude of fluxes

Bowen ratio energy balance method broke down when Bowen ratio approached -1, even though it might not be -1 precisely. Latent heat flux calculated became unreasonable. Sensible and latent heat were transported in opposite directions in near equilibrium. The denominator of equation 2.6 became vanishingly small as $\beta \rightarrow -1$ and the entire equation became undefined when β = -1. In this study, the condition was often encountered at dawn and dusk, when the available energy approached zero, which corroborated with Fritschen, 1965. Ohmura, 1982 stressed that the condition was also encountered during intense foehn wind or precipitation. The condition had also been observed under desert conditions, where latent heat fluxes were small (Malek et al., 1987) and at midday and early afternoon under cloudy conditions (Pruitt et al., 1987).

Figure 3.5 shows the diurnal variation of surface energy fluxes on 1st December, 2014. BREB method broke down at 200 hours and 2000 hours due to Bowen ratio (β) approaching -1. Sensible and latent heat fluxes were transported in opposite directions in near equilibrium indicating that BREB method could not quantify the fluxes coming from the surface. Temperature was the cause of this problem because temperature differences were negative (inversion period). During such periods, sensible heat was drawn from air which enhanced evapotranspiration. The same thing was observed in figure 3.7 from 1900 hours to 2300 hours. Bowen ratio approached -1 for those periods. Criteria given by inequality (2.12) was used to reject Bowen ratio data for those periods. The rejected data were then replaced by interpolation method as shown in figure 3.6 and figure 3.8 respectively.

It was observed that weak turbulent condition was also responsible for the breakdown of Bowen ratio during the nighttime period. The energy exchange processes between the surface and the atmosphere depend not only on the availability of energy and moisture in the soil, since these determine the energy partitioning between sensible and latent heat fluxes, but also on the existence of significant temperature and vapour pressure concentration gradients and turbulent atmosphere to carry the vapour and heat away from the surface to the atmosphere. At night the energy available for evapotranspiration is negligible and Oliver (1965) pinpointed that, lower wind speeds and stable atmospheric conditions suppressed turbulent diffusion of water vapour and consequently, surface energy exchange. Because of the aforesaid reasons, Foken et al., (1997) gave the opinion that data not satisfying conditions for a well-developed turbulent atmosphere should be eliminated from the BREB flux estimations, particularly, the wind at the lower level of measurement $U(Z_1)$ must be greater than 1m/s and $\Delta U > 0.3$m/s. The data used for this study buttressed this argument because the BREB method gave unacceptable results when adequate turbulent conditions were not met.

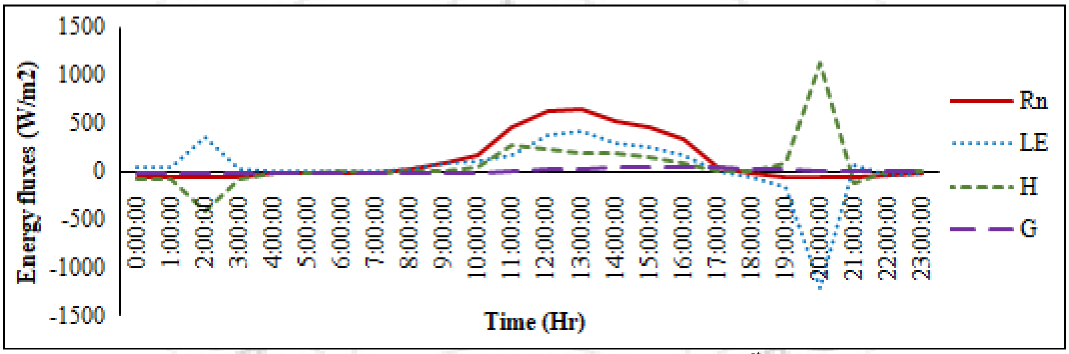

Figure 3.5: Diurnal variation of surface energy fluxes on 1st December, 2014

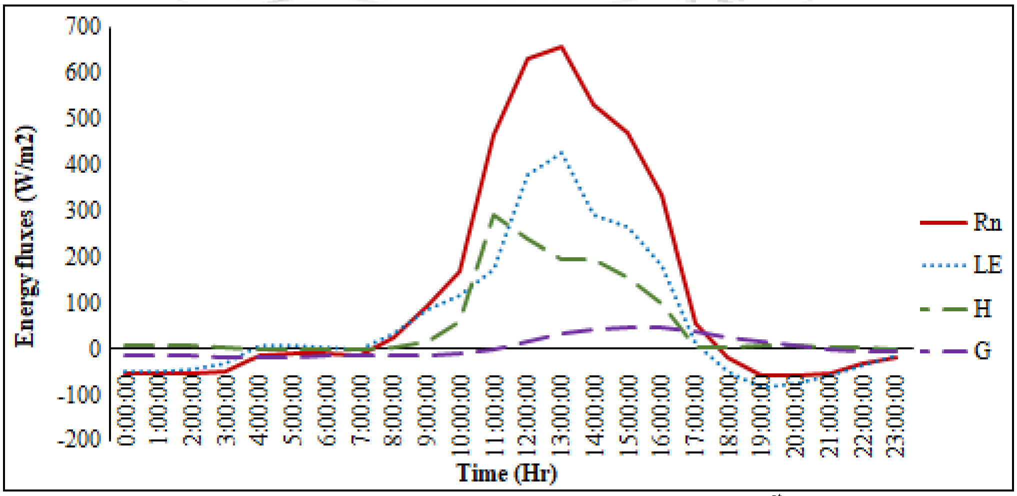

Figure 3.6: Modified diurnal variation of surface energy fluxes on 1st December, 2014.

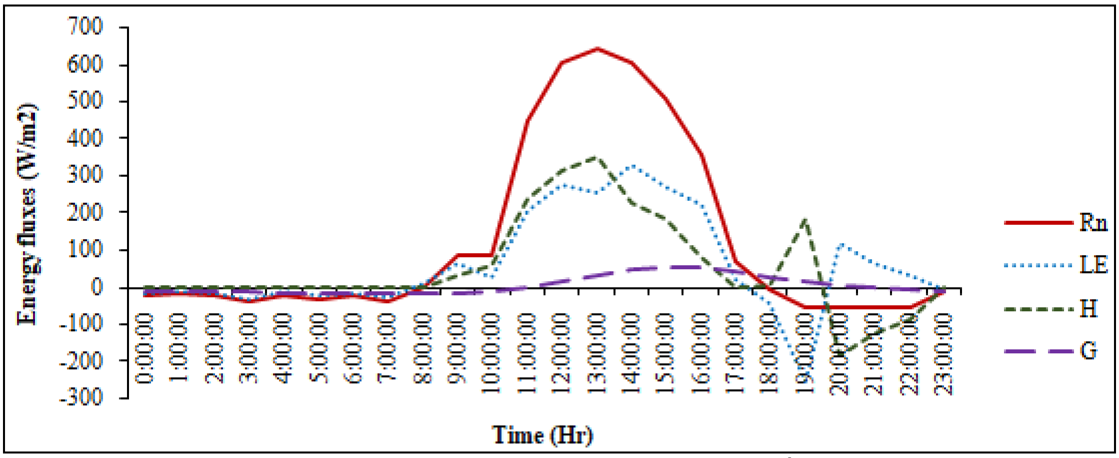

Figure 3.7: Diurnal variation of surface energy fluxes on 2nd December, 2014

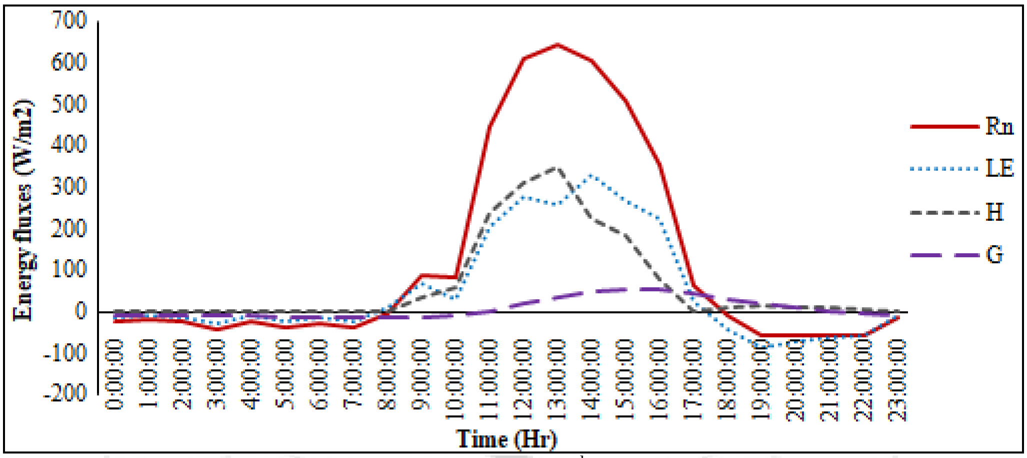

Figure 3.8: Modified diurnal variation of surface energy fluxes on 2nd December, 2014.

Table 3.2 shows the estimated fluxes for 01 December, 2014. From 0000 hours to 0300 hours, the temperature differences fell within the range of inequality (2.12), mainly because of inversion. Also, vapor pressure differences were small and approached the resolution limit of the sensor. Hence, the data for those periods were rejected. At 0700 hours, 1800 hours, 1900 hours, 2200hours and 2300hours that day, Bowen ratio broke down because the measurements gave wrong signs. At 2000, Bowen ratio approached -1 which was the major cause of its failure, and the measurement also gave wrong signs for the fluxes at the same time. Around 2100, temperature difference was within the range of inequality defined by (2.12), hence, Bowen ratio gave unacceptable flux estimates.

Table 3.2: A table showing an example of erroneously large values for turbulent fluxes calculated by the Bowen ratio energy balance method on 01 December, 2014

Time	Δe	D	<	ΔT	<	F	β	LE	H	Rn - G	Remark
0:00:00	0.024	-1.104	<	-0.645	<	0.318	-1.658	42.386	-80.174	-38.473	Rejected
1:00:00	0.023	-1.019	<	-0.665	<	0.308	-1.872	44.528	-83.377	-38.849	Rejected
2:00:00	0.030	-1.123	<	-0.508	<	0.204	-1.105	368.333	-407.166	-38.833	Rejected
3:00:00	0.017	-0.931	<	-0.472	<	0.396	-1.761	39.038	-68.752	-29.713	Rejected
4:00:00	0.034	-1.187	<	-0.175	<	0.140	-0.334	9.224	-3.082	6.142	Accepted
5:00:00	0.046	-1.374	<	-0.030	<	-0.047	-0.042	7.668	-0.324	7.345	Accepted
6:00:00	0.040	-1.291	<	0.027	<	0.036	0.043	4.745	0.202	4.946	Accepted
7:00:00	0.041	-1.303	<	0.038	<	0.024	0.060	-1.150	-0.069	-1.219	Rejected
8:00:00	0.052	-1.480	<	0.107	<	-0.153	0.131	32.735	4.278	37.013	Accepted
9:00:00	0.115	-2.456	<	0.397	<	-1.129	0.221	86.674	19.178	105.853	Accepted
10:00:00	0.109	-2.365	<	0.892	<	-1.038	0.524	116.943	61.282	178.225	Accepted
11:00:00	0.079	-1.895	<	2.097	<	-0.568	1.702	171.833	292.464	464.297	Accepted
12:00:00	0.140	-2.838	<	1.375	<	-1.511	0.632	376.669	238.218	614.887	Accepted
13:00:00	0.123	-2.584	<	0.888	<	-1.257	0.462	426.703	197.336	624.039	Accepted
14:00:00	0.104	-2.283	<	1.085	<	-0.956	0.670	291.818	195.500	487.317	Accepted
15:00:00	0.082	-1.936	<	0.753	<	-0.609	0.592	264.941	156.858	421.799	Accepted
16:00:00	0.100	-2.227	<	0.857	<	-0.900	0.548	184.100	100.849	284.949	Accepted
17:00:00	0.044	-1.348	<	0.102	<	-0.021	0.148	12.720	1.889	14.609	Accepted
18:00:00	0.129	-2.674	<	-0.218	<	-1.347	-0.109	-49.478	5.374	-44.104	Rejected
19:00:00	0.067	-1.711	<	-0.593	<	-0.384	-0.567	-168.575	95.517	-73.059	Rejected

20:00:00	0.063	-1.646 <	-0.930 <	-0.320	-0.946	-1203.371	1138.487	-64.884	Rejected
21:00:00	0.033	-1.176 <	-0.957 <	0.151	-1.866	62.429	-116.491	-54.062	Rejected
22:00:00	0.083	-1.956 <	-0.202 <	-0.629	-0.156	-34.387	5.365	-29.022	Rejected
23:00:00	0.085	-1.986 <	-0.073 <	-0.659	-0.055	-13.201	0.732	-12.468	Rejected

It should be noted that the fact that the temperature difference falls within the range of inequality represented by (2.12) does not mean that BREB method has totally failed, but it is a reasonable criterion for rejecting Bowen ratio values closed to -1.

Perez et al., (1999) gave the summary of the cases when BREB method fails (see table 2.1). It was observed in this study that the periods when BREB method was absolutely failed were the periods when there were wrong signs for the flux estimates and when Bowen ratio approached -1. These are shown in table 3.3.Conditions A and C (table 2.1) were satisfied in this study for the cases when BREB method failed i.e. when

$$R_n - G > 0 \text{ and } \Delta e > 0 \text{ then } \beta < -1 + |\varepsilon| \text{ and}$$
$$R_n - G < 0 \text{ and } \Delta e > 0 \text{ then } \beta > -1 - |\varepsilon|$$

When analysis was carried out on cases when BREB method fails (table 2.1), it was observed that when condensation occurred and the available energy was greater than zero, as seen in figure3.3, BREB method did not break down. Therefore, it could be concluded that condensation is not forbidden in BREB method but the process of condensation or precipitation removes water vapour from the atmosphere which makes water vapour difference (Δe) fall below magnitude of sensor-dependent error. Also turbulent fluxes are transported in opposite directions. These factors make Bowen ratio data rejection necessary.

Table 3.3: A typical example of cases when BREB method failed. 14th December, 2014

Time	Rn-G	Δe	ΔT	-1-|ε|	β	-1+|ε|	LE	H	Remark
0:00:00	-42.512	0.004	-1.025	-5.791	-16.834	3.791	2.685	-45.197	Works
1:00:00	-44.893	0.051	-0.660	-1.365	-0.825	-0.635	-255.949	211.056	Fails
2:00:00	-39.085	0.053	-0.328	-1.356	-0.401	-0.644	-65.271	26.186	Fails
3:00:00	-37.220	0.050	-0.512	-1.376	-0.659	-0.624	-109.148	71.928	Fails
4:00:00	-36.407	0.020	-0.640	-1.938	-2.058	-0.062	34.418	-70.824	Works
5:00:00	-34.311	0.025	-0.655	-1.736	-1.653	-0.264	52.549	-86.860	Fails
6:00:00	-33.116	0.015	-0.798	-2.223	-3.347	0.223	14.112	-47.228	Works
7:00:00	-34.864	0.012	-0.818	-2.584	-4.442	0.584	10.129	-44.993	Works
8:00:00	-7.472	0.060	-0.275	-1.314	-0.296	-0.686	-10.606	3.134	Fails
9:00:00	76.601	0.012	0.420	-2.508	2.172	0.508	24.153	52.449	Works
10:00:00	79.879	0.052	0.760	-1.359	0.935	-0.641	41.288	38.592	Works
11:00:00	392.357	0.067	0.962	-1.279	0.919	-0.721	204.496	187.861	Works
12:00:00	488.507	0.081	0.830	-1.230	0.656	-0.770	295.071	193.437	Works
13:00:00	534.658	0.068	0.835	-1.276	0.790	-0.724	298.716	235.942	Works
14:00:00	461.241	0.068	0.625	-1.276	0.591	-0.724	289.818	171.423	Works
15:00:00	371.521	0.094	0.452	-1.199	0.308	-0.801	284.131	87.390	Works
16:00:00	256.992	0.067	0.318	-1.280	0.306	-0.720	196.809	60.183	Works
17:00:00	20.131	0.080	-0.027	-1.235	-0.021	-0.765	20.572	-0.442	Works
18:00:00	-26.678	0.125	-0.270	-1.150	-0.139	-0.850	-30.967	4.289	Fails
19:00:00	-68.801	0.056	-1.005	-1.334	-1.150	-0.666	458.332	-527.134	Fails
20:00:00	-58.998	0.043	-1.443	-1.437	-2.160	-0.563	50.861	-109.859	Works
21:00:00	-51.544	0.032	-0.980	-1.588	-1.975	-0.412	52.884	-104.428	Works
22:00:00	-44.316	0.037	-0.982	-1.508	-1.710	-0.492	62.455	-106.771	Works
23:00:00	-40.059	0.040	-0.688	-1.472	-1.114	-0.528	351.011	-391.070	Fails

3.3 Boundaries on Bowen ratio around -1

When values of $\beta \approx -1$, flux values are extremely inaccurate. There is a need to find out which non-permissible range around -1 to consider. The excluded interval of β values, $-1-|\varepsilon| < \beta < -1+|\varepsilon|$ can be determined exactly using the dimensionless quantity described by equation (2.13). Air temperature was measured at the two levels with platinum resistant thermocouples (PRT) that give errors in the temperature gradient measurement of >0.01^{0}C, so $\delta\Delta T$ = 0.02^{0}C was assumed. The resolution of the humidity sensor yielded a vapor pressure resolution of less than ±0.01 kPa, therefore, a resolution of 0.02 kPa was assumed for Δe ($\delta\Delta e$ = 0.02). Then, taking into account the small variation of the psychrometric constant with temperature, on average 0.063 kPa^{0}C^{-1} between 0 and 30◦C, and the above values for $\delta\Delta e$ and $\delta\Delta T$, equation (2.13) becomes

$$\varepsilon = \frac{0.019}{\Delta e}$$

Therefore, the exclude interval of Bowen ratio values varies slightly because it depends on vapour pressure difference.

In table 3.3, when Bowen ratio failed from 1700hr to 1900hr, and considering other periods, it could be concluded that the excluded interval on Bowen ratio was $-1.3 < \beta < -0.7$. This corroborated with the criterion proposed by Ortega-Farias et al., 1996 and Unland et al., 1996. This was the range of values when β gave extremely inaccurate turbulent flux estimates in this study.

3.4 Sensitivity considerations

When reliable data are measured and not discarded, there still remains the question of how accurate the estimates of the computed values of the sensible and latent heat fluxes are. When an error analysis was carried out following other author's criteria (Fuchs and Tanner, 1970; Angus and Watts, 1984; Andreas and Cash, 1996; Perez et al., 1999), the relative uncertainties of the sensible and latent heat fluxes were obtained. These uncertainties showed how sensitive the estimates of LE and H were to uncertainties in the variables used to estimate them, Rn, G and β. The maximum relative uncertainty in β can be expressed as

$$\left|\frac{\delta\beta}{\beta}\right| = \frac{\delta\Delta T}{|\Delta T|} + \frac{\delta\Delta e}{|\Delta e|} \quad (3.1)$$

whereas, the relative uncertainties in LE and H are given, respectively, by

$$\left|\frac{\delta LE}{LE}\right| = \frac{\delta R_n + \delta G}{|R_n - G|} + \frac{\delta\beta}{|1+\beta|} \quad (3.2)$$

and

$$\left|\frac{\delta H}{H}\right| = \frac{\delta R_n + \delta G}{|R_n - G|} + \frac{\delta\beta}{|\beta(1+\beta)|} \quad (3.3)$$

A typical accuracy of ±5% in Rn is a reasonable choice taking into account the sensor accuracy and the errors related to the leveling of the sensor under normal conditions, which can be a considerable source of measurement errors (Linkosalo et al., 1996). The soil heat flux G is determined by adding the heat flux (F) measured with plates buried in the soil at 0.1m to the change of energy stored in the soil layer (ΔS) above the plate (Clothier et al., 1986). This storage term, calculated by measuring the change in the soil temperature (ΔTs) over the averaging period, is the most important term in G. It can represent up to 70–80% G, whereas F is usually 20–30% G. Then, taking into account the instrumental error of the soil heat flux plate and the overall accuracy of the thermistor used to measure Ts (in the worst case δΔTs = 0.2◦C), an average uncertainty in G of 30% was obtained. This error can be reduced with more accurate thermistors and by placing the heat flux plates as close to the soil surface as allowed by the soil type. For the cases not rejected but in which the values of the temperature or vapor pressure gradients are of the order of the resolution limits of the sensors, i.e., |Δe| ≈ δΔe or |ΔT| ≈ δΔT, eq. (3.1) shows that the relative uncertainty in β can be large (for example 100% for |δΔe| = |δΔT| = 0.04). This is the criterion used by some authors to assess whether the fluxes are reliable (Unland et al., 1996). However, a large relative uncertainty in β does not necessarily imply a large one in LE. As can be seen in equations (3.2) and (3.3), when Rn − G is close to 0, even a small uncertainty in Rn or G would give a large relative uncertainty in LE and H. Furthermore, if β is near −1, a small relative uncertainty in β would also give a large relative uncertainty in both energy fluxes.

The largest uncertainties appear during the night (table 3.4). Some cases have large relative uncertainties in β (higher than 100%) when β is near 0 (table 3.4, at 1700 hours). At other times there were cases with low relative uncertainties in β and large ones in LE and H when the value of Rn − G is close to 0 (for instance 2000 hours in table 3.4 above). Therefore, for reliable data it may be useful to limit the uncertainty in LE to a maximum value for considering the fluxes as correct. This limit may vary from 10% under ideal conditions (Sinclair et al., 1975; Kustas et al., 1996) to 20% for heterogeneous surfaces (Nie et al., 1992) or 60% depending on the β value (Angus and Watts, 1984). In this study, for reliable data and during the daytime period from 700 hours to 18 hours, the uncertainty in LE ranges from 10 to 30% whereas for H it is between 15 and 70%. The interval of β values corresponding to daytime period when fluxes are reliable and errors are minima can be a simple condition to be used in order to consider the fluxes measured by the BREB method as accurate.

Table 3.4: Estimated errors on different terms of equation (4.1) to (4.3). 14th December, 2014

Time	ΔT	Δe	δΔT/|ΔT|	δΔe/|Δe|	Rn-G	β	|δβ/β|	δLE/LE	|δH/H|
0:00:00	-1.025	0.004	0.020	5.119	-42.512	-16.834	5.139	5.307	0.168
1:00:00	-0.660	0.051	0.030	0.389	-44.893	-0.825	0.420	1.801	2.221
2:00:00	-0.328	0.053	0.061	0.381	-39.085	-0.401	0.442	0.086	0.528
3:00:00	-0.512	0.050	0.039	0.401	-37.220	-0.659	0.441	0.618	1.058
4:00:00	-0.640	0.020	0.031	1.002	-36.407	-2.058	1.033	1.761	0.728
5:00:00	-0.655	0.025	0.031	0.787	-34.311	-1.653	0.817	1.793	0.976
6:00:00	-0.798	0.015	0.025	1.307	-33.116	-3.347	1.332	1.605	0.273
7:00:00	-0.818	0.012	0.024	1.692	-34.864	-4.442	1.716	1.925	0.208
8:00:00	-0.275	0.060	0.073	0.335	-7.472	-0.296	0.408	-1.033	-0.625
9:00:00	0.420	0.012	0.048	1.612	76.601	2.172	1.659	1.083	0.470
10:00:00	0.760	0.052	0.026	0.383	79.879	0.935	0.410	0.181	0.195
11:00:00	0.962	0.067	0.021	0.298	392.357	0.919	0.319	0.199	0.213
12:00:00	0.830	0.081	0.024	0.246	488.507	0.656	0.270	0.164	0.220
13:00:00	0.835	0.068	0.024	0.295	534.658	0.790	0.319	0.205	0.243
14:00:00	0.625	0.068	0.032	0.295	461.241	0.591	0.327	0.197	0.281
15:00:00	0.452	0.094	0.044	0.212	371.521	0.308	0.257	0.147	0.283
16:00:00	0.318	0.067	0.063	0.299	256.992	0.306	0.362	0.188	0.380
17:00:00	-0.027	0.080	0.750	0.251	20.131	-0.021	1.001	0.654	1.655
18:00:00	-0.270	0.125	0.074	0.160	-26.678	-0.139	0.234	0.276	0.510
19:00:00	-1.005	0.056	0.020	0.357	-68.801	-1.150	0.377	2.898	2.522
20:00:00	-1.443	0.043	0.014	0.466	-58.998	-2.160	0.480	0.864	0.384
21:00:00	-0.980	0.032	0.020	0.628	-51.544	-1.975	0.648	0.574	0.254
22:00:00	-0.982	0.037	0.020	0.543	-44.316	-1.710	0.563	1.240	0.677
23:00:00	-0.688	0.040	0.029	0.505	-40.059	-1.114	0.534	5.054	4.521

Figure 3.9 shows average hourly relative uncertainties (%) of the Bowen ratio (δβ/β), the latent heat flux (δLE/LE) and the sensible heat flux (δH/H) for the reliable data measured by the BREB method on 1st December, 2014. Large relative uncertainties were observed during nighttime period but the reverse occurred during the daytime period. During daytime hour (1100 hour), when Bowen ratio was large, relative errors were small due to significant vapour pressure concentration gradient and turbulent mixing.When Bowen ratio (β) values were small, there were consistent partitioning of latent and sensible heat fluxes. The reason was that high latent heat flux values have low relative errors (Angus and Watts, 1984; Foken et al., 1996). Where there were large Bowen ratio values, the errors were mainly due to inconsistent vapour pressure differences, the estimated fluxes were spurious with large relative errors and were prone to rejection. The periods when relative errors were small occurred on wet, high radiation days when Bowen ratio values were small and rejections were few. During very dry conditions with limited moisture in the soil, latent heat error increases with large β because vapour pressure differences are very small.

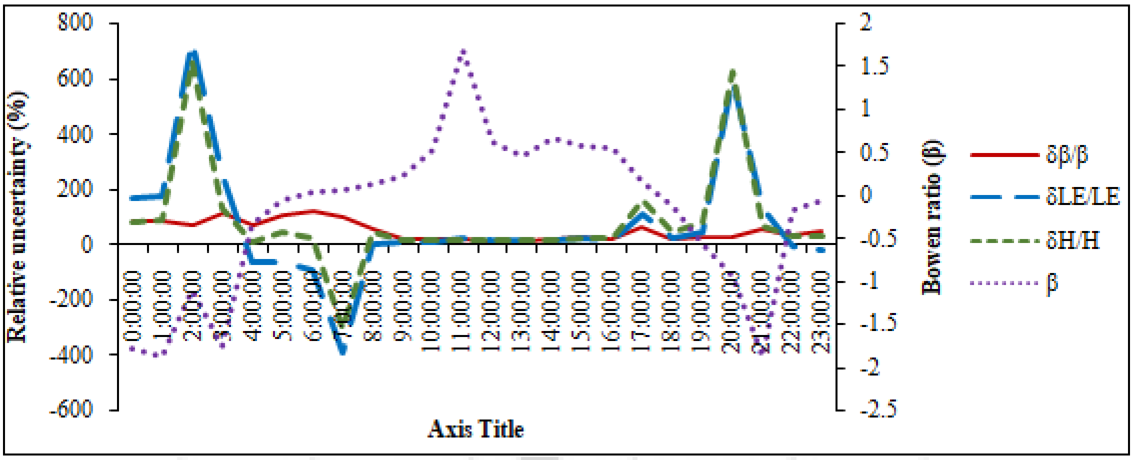

Figure 3.9: Average hourly relative uncertainties (%) of the Bowen ratio (δβ/β), the latent heat flux (δLE/LE) and the sensible heat flux (δH/H) for the reliable data measured by the BREB method on 1st December, 2014

3.5 Criteria developed for rejecting erroneous Bowen ratio values

The result of this study shows that when temperature and vapour pressure differences are small and approach the resolution limit of the sensors used, turbulent fluxes become unreliable. Large uncertainties are introduced into the fluxes. Consequently, data rejection is necessary when temperature and vapour pressure differences approach the resolution of the sensors particularly, when $\Delta e < 0.05$. This was the first criterion used to reject spurious data in this study.

Secondly, when analysis on the excluded interval of β around -1 was performed, it was observed that the interval for which β gave extremely inaccurate flux estimates varied slightly, owing to the dependence of error interval (ε) on vapour pressure differences. Considering the extreme values, β values gave unreasonable flux estimates when $-1.3 < \beta < -0.7$. This was the second criterion used to reject counterfeit Bowen ratio data.

Thirdly, it was observed in this study that the periods when β values approached -1, and thus, gave unreasonable flux estimates correspond to the interval $-0.02 < \Delta e + \Upsilon \Delta T < 0.02$. This criterion has also been developed to reject spurious data for which $\beta \rightarrow -1$. It should be noted that if the second criterion above can be applied in arid and semiarid parts of the world, this criterion should also be applicable to those regions.

Finally, the interval of β values corresponding to daytime period when fluxes are reliable can be a simple condition to be used in order to consider the fluxes measured by the BREB method as accurate. In figure 3.9, the interval corresponds to $-0.5 < \beta < 0.5$. This interval, as seen in fig.3.9, gave minimum relative errors in the estimated turbulent fluxes.

4. Conclusion

There are cases when the BREB method fails to provide reliable measurements of evapotranspiration, so certain criteria for rejecting inaccurate data are required. With the present analysis it is easy to recognize the failure of the method in determining the surface fluxes. Results show that the periods when BREB method fails in semi-arid regions due to advection correspondto the periods when it fails in a tropical humid region as a result of inversion. The criteria used to reject spurious data have been found to depend on the physical inconsistency of the flux-gradient definition and on the resolution limits of the sensors. If the temperature and vapor pressure gradients and the resolution limits of the sensors are known, spurious data obtained from the BREB method would easily be recognized. Extremely inaccurate fluxes occurring when Bowen ratio approached -1 were easily discarded by excluding data for which $-0.02 < \Delta e + \Upsilon \Delta T < 0.02$ as developed in this study. Errors due to small gradients were taken into consideration by rejecting data for which $\Delta e < 0.05$ as this would introduce high uncertainty into latent heat flux estimated. It was observed that data corresponding to early morning, late afternoon and precipitation period often had to be rejected. The criteria mentioned above can be applied to situations of BREB method measurement particularly for the case with similar sensor errors.

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