UNIVERSITÄT BAYREUTH

Abt. Mikrometeorologie

Error analysis of the modified Bowen ratio method

Heping Liu

Arbeitsergebnisse

Nr. 04

Bayreuth, 02 1999

Arbeitsergebnisse, Universität Bayreuth, Abt. Mikrometeorologie, Print, ISSN 1614-8916
Arbeitsergebnisse, Universität Bayreuth, Abt. Mikrometeorologie, Internet, ISSN 1614-8924
http://www.bayceer.uni-bayreuth.de/mm/

Eigenverlag: Universität Bayreuth, Abt. Mikrometeorologie
Vervielfältigung: Druckerei der Universität Bayreuth
Herausgeber: Prof. Dr. Thomas Foken

Universität Bayreuth, Abteilung Mikrometeorologie
D-95440 Bayreuth

Error analysis of the modified Bowen ratio method

Heping Liu*

Department of Micrometeorology, University of Bayreuth, D-95440 Bayreuth, Germany

Abstract The sensible and latent heat fluxes are obtained, using the modified Bowen ratio method (MBR) and Bowen ratio/Energy balance method (BREB) with the data of LINEX-97/1 and LITFASS-1998 experiments. The error analysis of MBR and the error comparisons between both methods are also made in detail by a lot of numerical experiments and the measured data. The results illustrate that the MBR, compared with the BREB, can obtain higher accurate results with errors of less than ±10% for sensible heat flux and less than ±20% for latent heat flux.

1. Introduction

The Bowen ratio/Energy balance (BREB) method has been extensively used in micrometeorology, agrometeorology, forest meteorology, and other studies on boundary layer meteorology since it was published by Bowen in 1926 (e.g., in the last years, Lindroth and Halldin, 1990; Dugas et al., 1991; Bernhofer, 1992; Nie and Kanemasu, 1992; Dugas et al., 1993; Barr et al., 1994; Gay et al., 1996). It is generally accepted to obtain sensible and latent heat fluxes in many applications mainly because of its simple system with the measurements of two level dry and wet temperatures, the measurements of net radiation and soil heat flux. However, it could occasionally produce large errors because of its theoretical limitations. One of the reasons is the non-closure of the surface energy balance which leads to inaccuracies of BREB fluxes (Horst and Weil, 1992; Foken and Oncley, 1995; Panin et al., 1996; Wicke and Bernhofer, 1996; Foken et al., 1997a). Furthermore, when Bowen ratio approaches –1 or is exactly –1, the BREB can give rise to unacceptable errors; therefore, many data are excluded when Bowen ratios are between –1.25 and –0.75 (Ohmura, 1982; Cellier and Olioso, 1993). Based on the above points, Liu and Foken (1999a) have proposed a new the modified Bowen

*) Permanent address: Department of Geophysics, Peking University, 100871 Beijing, China

ratio (MBR) method, which avoids the above limitations, especially inaccuracies caused by the non-closure of the surface energy balance. Some results and brief error analysis have been shown in Liu and Foken (1999a); in this paper, some different results and more detailed error analysis are given here to show its possible advantages and disadvantages. Finally the modified Bowen ratio system with a sonic anemometer and two level psychrometers is recommended to obtain sensible and latent heat fluxes.

2. Modified Bowen ratio method

The modified Bowen ratio system includes a sonic anemometer to calculate sensible heat flux from sonic-derived buoyancy flux and two level psychrometers to measure Bowen ratio.

Assuming similarity of the eddy diffusivities of heat and water vapor, the Bowen ratio may be measured by two level psychrometers, and can be rewritten in finite differences as (e.g., Fuchs and Tanner, 1970; Ohmura, 1982; Foken et al., 1997b):

$$Bo = \frac{c_p}{\lambda} \cdot \frac{\Delta T}{\Delta q} \tag{1}$$

Eddy correlation measurements of the latent heat flux are very complicated and expensive (Moncrieff et al., 1997; Foken et al., 1998), but eddy correlation method to determine the friction velocity and the sensible heat flux is not very expensive (cheaper than net radiometer with a moderate accuracy) (Foken, 1998a). On the other hand, because more and more sonic anemometers are widely used in boundary layer meteorology, one of the aims of the modified Bowen ratio method is the wish to make full use of the resource of sonic anemometer to measure buoyancy flux and then to calculate sensible heat flux. Some theoretical backgrounds have already been well established (e.g., Kaimal and Businger, 1963; Schotanus et al., 1983). If sonic determined temperature is obtained, then the buoyancy flux can be written as

$$H_S = \rho c_p \overline{w'T_S'} \tag{2}$$

If sonic-derived temperature can be determined from the vertical axis (e.g., Kaijo Denki DAT 300/A), the relationship between the buoyancy flux and the sensible heat flux can be rewritten as followings after considering velocity and moisture transformation (e.g., Kaimal and Businger, 1963; Schotanus et al., 1983),

$$\overline{w'T_S'} = \overline{w'T'} + 0.51\overline{T} \cdot \overline{w'q'} - 2\frac{\overline{T} \cdot \overline{u}}{c^2}\overline{u'w'} \qquad (3)$$

The first term of the right-hand side of Equation (3) is the sensible heat obtained by the eddy correlation method ($\overline{w'T'}$) with a thin wire thermometer. In the MBR, sensible heat flux is determined using Equation (3), and written as $(\overline{w'T'})_c$. If we substitute $\overline{w'q'}$ in Equation (3) by $\overline{w'q'} = c_p /(\lambda \cdot Bo) \cdot \overline{w'T'}$, the following equation can be easily obtained,

$$H_{MBR} = \rho c_p (\overline{w'T'})_c = \rho c_p (\overline{w'T_S'} + 2\frac{\overline{T} \cdot \overline{u}}{c^2} \cdot \overline{u'w'}) /(1 + \frac{0.51 \cdot \overline{T} \cdot c_p}{\lambda \cdot Bo}) \qquad (4)$$

Originally, Bowen ratio is defined as:

$$Bo = \frac{H}{\lambda E} \qquad (5)$$

Thus, if the sensible heat flux H in Equation (5) is obtained according to Equation (4) and the Bowen ratio according to Equation (1), then latent heat flux can be derived from Equation (5),

$$\lambda E_{MBR} = \frac{H_{MBR}}{Bo} \qquad (6)$$

Equation (3) is based on a sonic anemometer that measures temperature along the vertical axis (e.g., Kaijo Denki DAT-300/A). New types of sonic anemometers (e.g., CSAT3) calculate the temperature from an average value of temperatures measured in three paths; therefore a new equation has been derived to obtain H_{MBR} (Liu and Foken, 1999b) as follows,

$$H_{MBR} = \rho c_p (\overline{w'T'})_c = \rho c_p (\overline{w'T_S'} + \frac{2\overline{T}}{c^2}(\overline{u} \cdot \overline{u'w'} \cdot A + \overline{v} \cdot \overline{v'w'} \cdot B)) /(1 + \frac{0.51 \cdot \overline{T} \cdot c_p}{\lambda \cdot Bo}) \qquad (7)$$

Where A and B are correct factors, see Liu and Foken (1999b) for detail.

3. LINEX-97/1 experiment and LITFASS-1998 experiment

During June 1997, the LINEX-97/1 experiment took place at the boundary layer measuring field near Falkenberg ($52^\circ 10'02''N$, $14^\circ 07'24''E$) which is about 5km south of the Lindenberg Meteorological Observatory of the German Weather Service. The topography of the whole area is fairly flat, and was covered by short grass during the experiment period (Foken 1998b).

At the site, an assortment of micrometeorological instrumentation for mean and eddy correlation measurements were installed. The list of the instrumentation used is given in Table 1. More details about the experiment site and the additional meteorological measurements can be found in Foken (1998b). In this study, we used only the turbulence data collected by the Kaijo-Denki DAT-300 sonic anemometer and Lyman-alpha hygrometer at 2m. In order to ensure the quality of turbulence data, the QA/QC scheme is used (Foken and Wichura 1996). The wind, dry- and wet- temperatures were measured at different heights on a 10-m tower, only the data in 0.5 m and 2 m are used for the present study. The net radiation was obtained by measurements of all radiation components at 2m above the grass, and the soil heat flux by plates at 0.05m below the surface.

Table 1. Instrumentation used during LINEX-97/1 and LITFASS-1998

Height (m)	Devices	Experiments
$0.5^{*)}$, $2.0^{*)}$	Climatronics anemometer model F 460	LINEX-97/1, LITFASS-1998
$0.5^{*)}$, $2.0^{*)}$	'Frankenberger' psychrometer	LINEX-97/1, LITFASS-1998
2.0	Kaijo-Denki DAT 310/A by Hanafusa et al. (1982)	LINEX-97/1
2.0	CSAT3, Campbell Sci.	LITFASS-1998
2.0	fast response 12 μm platinum wire, AIR	LINEX-97/1, LITFASS-1998
2.0	Lyman-alpha hygrometer by Foken et al.(1998)	LINEX-97/1
2.0	Krypton Hygrometer, Campbell Sci.	LITFASS-1998
2.0	Albedometer CM14 (short wave radiation)	LINEX-97/1, LITFASS-1998
2.0	Net radiometer by Schulze (sum of short and long wave radiation)	LINEX-97/1
2.0	Eppley net-pyschometer, modified according to Philipona et al. (1995)	LITFASS-1998
-0.05	Soil heat flux plate Rimco HP3	LINEX-97/1, LITFASS-1998

*) Height above zero-plane displacement

During June 1998, the LITFASS-1998 experiment was conducted in the same location, which was covered with less than 10% of short maize, about 10cm in height. A CSAT3 sonic anemometer, a platinum thermometer, and a Kypton hygrometer were used to obtain sensible and latent heat fluxes at 2m, and a 6-m mast with 5 level psychrometers was employed to measure the Bowen ratios (See Table 1). More details about this experiment can be found in Foken (1999).

4. Results and Discussions

In processing the turbulence data, in order to ensure the turbulence data with high quality, the quality test scheme is used, which is described by Foken and Wichura (1996). In order to confirm Bowen ratios were correctly measured, we compared the Bowen ratios in Equation (1) with Equation (5) where H and λE are the values of the eddy correlation measurement, i.e., H_{EC} and λE_{EC}, respectively. Figure 1 illustrates the comparison results for the grassland at LINEX-97/1 field experiment on 16, 17, 18 June 1997. Over the grassland, the Bowen ratios are from about −1.5 to about 0.9. The Bowen ratios measured by the Bowen ratio system are in agreement with those by the eddy correlation system, and the Bowen ratio system has measurement errors of around ±10%.

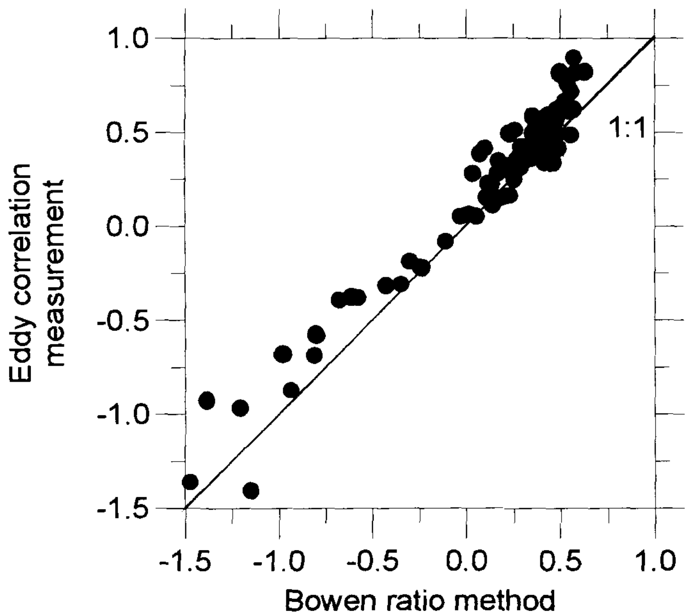

Fig. 1. Comparison of Bowen ratios between by Equation (1) and Equation (5) where H and λE are measured by eddy correlation method for the grassland at LINEX-97/1 field study on 16, 17 and 18 June 1997.

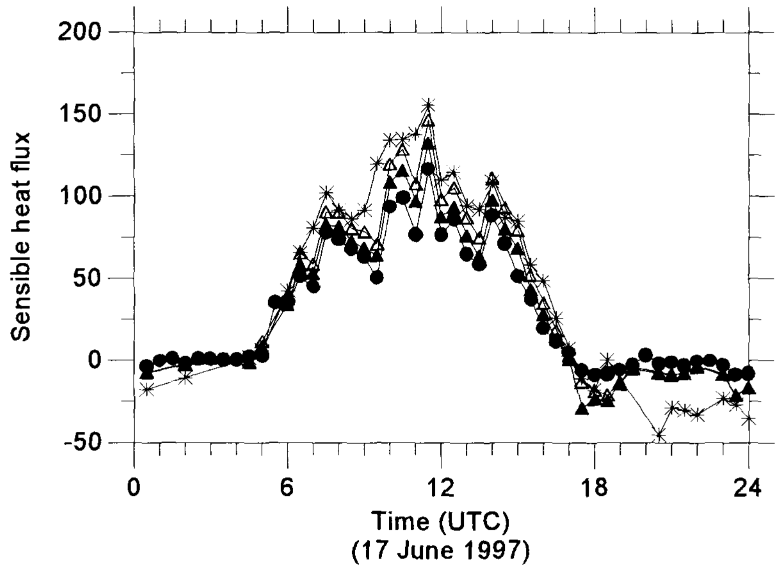

Figure 2. Comparison of heat fluxes for the grassland at LINEX-97/1 field study on 17 June 1997.

(*, H_{BREB} ; Δ, H_S ; ▲, H_{MBR} ; ●, H_{EC})

Figure 2 is the comparisons of H_{BREB}, H_S, H_{MBR} and H_{EC} for the grassland at LINEX-97/1 field study on 17 June 1997. The results show that H_{BREB} is around 35% higher than H_{EC}, and much scattering during the nighttime; H_S is around 20% higher that H_{EC}; H_{MBR} is around 10% higher than H_{EC}. Form the results, the sensible heat flux from the buoyancy flux after considering the velocity and humidity transformation can be fully accepted for general uses.

Figure 3 is the comparison of latent heat fluxes obtained by three different methods of BREB, MBR, and EC. Similar to the above analysis, λE_{BREB} is around 55% higher than λE_{EC}, but λE_{MBR} is about 20% higher than λE_{EC}.

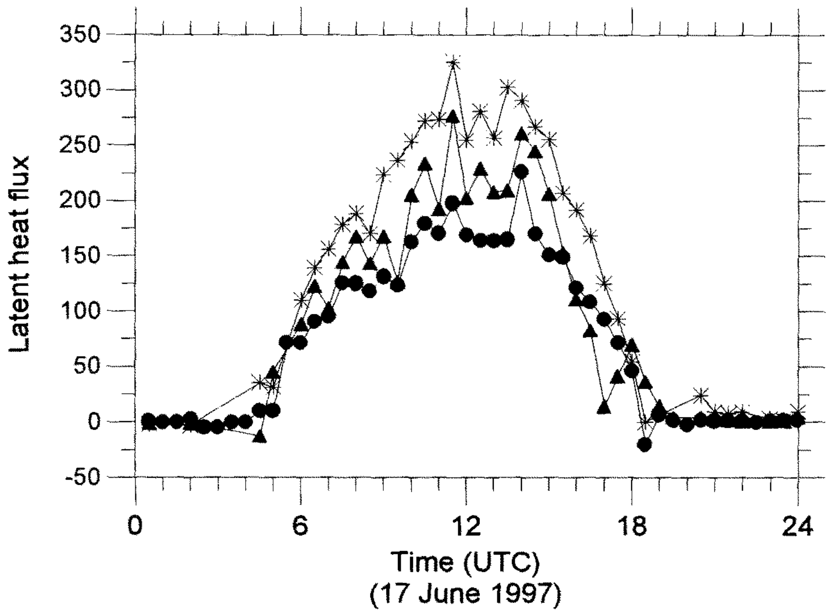

Figure 3. Comparison of latent heat fluxes for the grassland at LINEX-97/1 field study on 17 June 1997.

(*, λE_{BREB} ; ▲, λE_{MBR} ; •, λE_{EC})

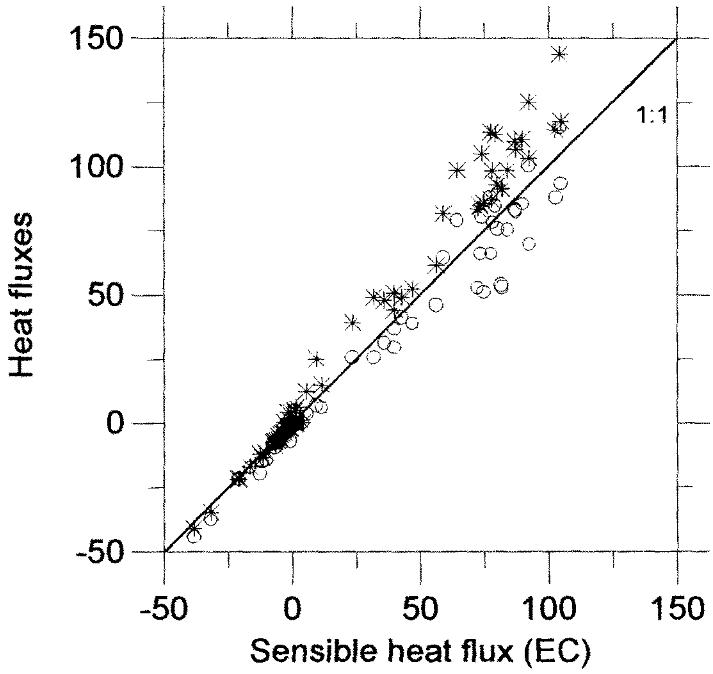

Figure 4. Comparison of heat fluxes at LITFASS-98 field study on 2, 3, 4 and 6 June 1998.

(*, H_S ; o, H_{MBR})

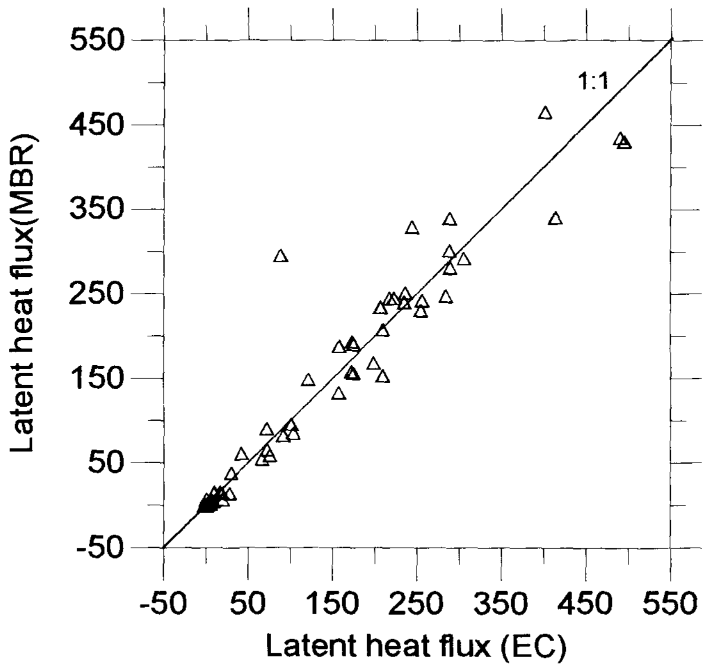

Figure 5. Comparison of latent heat fluxes between λE_{MBR} and λE_{EC} at LITFASS-98 field study on 2, 3, 4 and 5 June 1998.

During the LITFASS-1998 field study on June 1998, a CSAT3 sonic anemometer, a platinum thermometer, and a Krypton hygrometer were used to obtain sensible and latent heat fluxes. As previously mentioned, because the difference in obtaining sonic derived temperature between a Kaijo Denki DAT300/A sonic anemometer and a CSAT3 sonic anemometer, a new equation has been derived to get sensible heat flux from the buoyancy flux (Liu and Foken, 1999b) as Equation (7). Figure 4 and Figure 5 are the comparisons between H_S, H_{MBR} and H_{EC}, between λE_{MBR} and λE_{EC}, respectively.

In general, from the above results of the both experiments, H_{MBR} has a good agreement with H_{EC}, and H_{MBR} has errors of less than 10%. The latent heat flux λE_{MBR} is also in good agreement with λE_{EC}, and λE_{MBR} has errors of less than ±20%.

5. Error analysis

a. Error analysis of MBR

The error of sensible and latent heat fluxes by the modified Bowen ratio method can be obtained according to Equation (4) and Equation (6):

$$\frac{\delta H_{MBR}}{H_{MBR}} = \frac{\dfrac{\delta \overline{w'T_S'}}{\overline{w'T_S'}}}{1+2\cdot\dfrac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\dfrac{\overline{w'u'}}{\overline{w'T_S'}}} + \frac{\dfrac{\delta \overline{w'u'}}{\overline{w'u'}}}{1+\dfrac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\dfrac{\overline{w'T_S'}}{\overline{w'u'}}} + \frac{\dfrac{\delta \overline{T}}{\overline{T}}}{1+\dfrac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\dfrac{\overline{w'T_S'}}{\overline{w'u'}}} + \frac{\dfrac{\delta \overline{u}}{\overline{u}}}{1+\dfrac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\dfrac{\overline{w'T_S'}}{\overline{w'u'}}}$$
$$+\frac{\dfrac{\delta Bo}{Bo}}{1+\dfrac{\lambda\cdot Bo}{0.51\cdot\overline{T}\cdot c_p}} + \frac{\dfrac{\delta \overline{T}}{\overline{T}}}{1+\dfrac{\lambda\cdot Bo}{0.51\cdot\overline{T}\cdot c_p}} \tag{8}$$

$$\frac{\delta\lambda E_{MBR}}{\lambda E_{MBR}} = \frac{\delta Bo}{Bo} + \frac{\delta H_{MBR}}{H_{MBR}} \tag{9}$$

The notation δx refers to the error on operator x. From Equation (8), we can see that the error of H_{MBR} is nonlinearly dependent upon the measurement errors of $\overline{w'T_S'}$, the friction velocity u_*, the Bowen ratio Bo, the mean temperature $\overline{T}$, and the mean wind speed $\overline{u}$. Furthermore, the values of the factors of $1+2\cdot\dfrac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\dfrac{\overline{w'u'}}{\overline{w'T_S'}}$, $1+\dfrac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\dfrac{\overline{w'T_S'}}{\overline{w'u'}}$, and $1+\dfrac{\lambda\cdot Bo}{0.51\cdot\overline{T}\cdot c_p}$ in Equation (8) affect greatly the values of the error of H_{MBR}.

(1) Numerical experiments

In order to test the contribution of the error of each term in the right hand of Equation (8) to the total error under different conditions, and to find out which conditions should be avoided when using Equation (4) to calculate sensible heat flux from buoyancy flux, the following numerical experiments are made. In the following numerical experiments, it is assumed that u_*=0.1$\bar{u}$, $\frac{\delta \overline{w'T_s'}}{\overline{w'T_s'}}$= ±5% when $|\overline{w'T_s'}| > 0.05$ K·m/s, $\frac{\delta \overline{w'u'}}{\overline{w'u'}}$= ±5% when -$\overline{w'u'}$>0.005 m^2/s^2 (the data with u_*<0.07 m/s have been excluded), $\frac{\delta Bo}{Bo}$= ±5% when $Bo \neq 0.0$, $\frac{\delta \bar{T}}{\bar{T}}$= ±0.05%, and $\frac{\delta \bar{u}}{\bar{u}}$= ±5% when $\bar{u}$>0.7 m/s due to u_*>0.07 m/s.

From the numerical experiments, we have found that the factor $\left|1+\frac{\lambda \cdot Bo}{0.51 \cdot \bar{T} \cdot c_p}\right|$ in the last two terms of right hand side (R.H.S) of Equation (8) is greater than 1 when Bowen ratio is not around zero. The error of the last term of R.H.S of Equation (8) can be ignored because of the small value of the error of the temperature (±0.05%). The errors of the last two terms of right hand of Equation (8) can be less than ±1%. However, when Bowen ratios are around 0, the fifth term of R.H.S of Equation (8) can produce large error because the values of $1+\frac{\lambda \cdot Bo}{0.51 \cdot \bar{T} \cdot c_p}$ can be much less than 1 or even approach zero. Table 2 illustrates some examples of the errors when Bowen ratio is around zero. Actually when Bowen ratio is close to zero (positive and negative), it means that sensible heat flux is close to zero from Equation (5). Under this condition, sensible and latent heat fluxes can be positive and negative, namely the atmosphere stratification is changing, which does not satisfy the measurement conditions implied by the similarity theory. From the numerical experiment results, these conditions only occur when Bowen ratios are between –0.15 and 0.05; therefore we suggest that the fluxes, H_{MBR}, should be excluded when the Bowen ratios are between –0.15 and 0.05. This criterion will be also confirmed by the measured data.

Table 2. Some examples of results with large error due to the Bowen ratio

$\overline{T}$ (K)	Bo	$1+\lambda \cdot Bo/(0.51\cdot \overline{T}\cdot c_p)$	IV (%)	V (%)
280.0	-0.05	0.1284	77.9	0.4
285.0	-0.05	0.1452	69.0	0.4
290.0	-0.05	0.1584	63.0	0.3
295.0	-0.05	0.1727	58.0	0.3

From the numerical solutions, when $\overline{w'T_S'}$<0.0 (at least less than –0.05 K·m/s), it is shown that the factor $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$ is greater than 1 and the factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$ is much great 1(normally greater than 10). When $\overline{w'T_S'}$ >0.0 (at least greater than 0.05 K·m/s), the factor $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$ is less than 1, but close to 1 and the factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$ is much less than –1 (normal less than –10). Because the factor $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$ is much close to 1 in both conditions, then the error of the first term is nearly equal to the measurement error of $\overline{w'T_S'}$. The sum of the error of the second, third and fourth terms is too small to be ignored in both conditions; therefore the sum of the error of the first four terms is nearly equal to the measurement error of $\overline{w'T_S'}$ (i.e., ±5% at present study).

However, when $\overline{w'T_S'}$ is around zero, it can make the magnitudes of $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$ and $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$ very small. Even if we don't consider that the measurement error of $\overline{w'T_S'}$ will not increase when $\overline{w'T_S'}$ is around zero, and will be taken as ±5% as usual, the sum of the error of the first four terms can be very large. The results of the numerical experiments indicate that all the values which cause large errors are between –0.001 and 0.002 k·m/s; Some examples of the results with large errors are shown in Table 3. Therefore we suggest that the data with the value between at least between –0.001 and 0.002 K·m/s should be excluded. This criterion will be also confirmed by the measured data.

Table 3. Some examples of the results with large errors due to $\overline{w'T'_s}$.

$\overline{u}$ (m/s)	$\overline{w'T'_S}$ (k·m/s)	$1+2\cdot\frac{\overline{T}\cdot\overline{u}}{c^2}\cdot\frac{\overline{w'u'}}{\overline{w'T'_S}}$	$1+\frac{c^2}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T'_S}}{\overline{w'u'}}$	I (%)	II (%)	III (%)	IV (%)
1.2	0.0001	0.1424	-0.17	35.1	-30.1	-0.3	-30.1
1.5	0.0002	0.1625	-0.19	30.8	-25.8	-0.2	-25.8
1.8	0.0004	0.2764	-0.38	18.1	-13.1	-0.1	-13.1
2.0	0.0005	0.2059	-0.26	24.3	-19.3	-0.2	-19.3
2.2	0.0006	0.1193	-0.14	41.9	-36.9	-0.4	-36.9

(2) Data calculation

Based on the above numerical experiments, we have calculated the error magnitudes of all terms in Equation (8) and total error with $\frac{\delta\overline{w'T'_S}}{\overline{w'T'_S}}$ = ±5% when $\left|\overline{w'T'_S}\right| > 0.05$ K·m/s, $\frac{\delta\overline{w'u'}}{\overline{w'u'}}$ = ±5% when $-\overline{w'u'}$>0.005 m^2/s^2 (the data with u_*<0.07 m/s have been excluded), $\frac{\delta Bo}{Bo}$ = ±5% when $Bo \neq 0.0$, $\frac{\delta\overline{T}}{\overline{T}}$ = ±0.05%, and $\frac{\delta\overline{u}}{\overline{u}}$ = ±5% when $\overline{u}$>0.7 m/s due to u_*>0.07 m/s (only the positive error values are used for the calculation) using the data of LINEX-97/1 field study over the grassland on 16, 17 and 18 June 1997. Here u_* is taken to be the measured value instead of using u_*=0.1$\overline{u}$.

As examples, Table 4 shows the error magnitudes of all terms and total error in Equation (8) using the data of 16 June 1997. In general, the total error of H_{MBR} could be from ±5% to ±10% under the condition of the above given measurement errors of the instruments.

Table 4. The error magnitudes of each term in Equation (8) and the total error using the data of LINEX-97/1 field study over the grassland on 16 June 1997.

Time (UTC)	Bowen Ratio	I %	II %	III %	IV %	V %	VI %	Total %
0030	1.73	4.96	.04	.00	.04	.32	.00	5.36
0230	1.61	4.95	.05	.00	.05	.35	.00	5.41
0300	1.56	4.91	.09	.00	.09	.36	.00	5.45
0330	-1.43	4.64	.36	.00	.36	-.42	.00	4.94
0400	-.19	7.23	-2.22	-.02	-2.22	-4.35	-.02	-1.60
0430	-.07	11.13	-6.09	-.06	-6.09	-56.23	-.28	-57.62
0500	.13	5.26	-.26	.00	-.26	3.04	.02	7.79
0530	.34	5.13	-.13	.00	-.13	1.47	.01	6.35
0600	.39	5.17	-.17	.00	-.17	1.31	.01	6.14
0630	.39	5.17	-.16	.00	-.16	1.29	.01	6.13
0700	.42	5.16	-.16	.00	-.16	1.23	.01	6.07
0730	.46	5.16	-.16	.00	-.16	1.13	.01	5.97
0800	.56	5.10	-.10	.00	-.10	.96	.00	5.86
0830	.45	5.07	-.07	.00	-.07	1.15	.01	6.08
0900	.46	5.12	-.12	.00	-.12	1.13	.01	6.02
0930	.49	5.07	-.07	.00	-.07	1.08	.01	6.01
1000	.57	5.08	-.08	.00	-.08	.94	.00	5.87
1030	.55	5.06	-.06	.00	-.06	.97	.00	5.91
1100	.49	5.10	-.10	.00	-.10	1.07	.01	5.98
1130	.53	5.07	-.07	.00	-.07	1.01	.01	5.94
1200	.37	5.11	-.11	.00	-.11	1.38	.01	6.28
1230	.48	5.07	-.07	.00	-.07	1.11	.01	6.04
1300	.49	5.08	-.08	.00	-.08	1.09	.01	6.02
1330	.37	5.07	-.07	.00	-.07	1.37	.01	6.31
1400	.43	5.05	-.05	.00	-.05	1.22	.01	6.18
1430	.36	5.14	-.14	.00	-.14	1.40	.01	6.27
1500	.39	5.13	-.13	.00	-.13	1.34	.01	6.21
1530	.42	5.12	-.12	.00	-.12	1.25	.01	6.13
1600	.24	5.26	-.26	.00	-.26	2.00	.01	6.75
1630	.30	5.29	-.28	.00	-.28	1.65	.01	6.37
1700	.19	5.84	-.84	-.01	-.84	2.43	.01	6.59
1730	.02	-14.30	19.42	.19	19.42	7.63	.04	32.39
1800	-.24	4.71	.29	.00	.29	-3.31	-.02	1.97
1830	-.61	4.90	.10	.00	.10	-1.07	-.01	4.02
1930	-1.39	4.98	.02	.00	.02	-.44	.00	4.58
2000	-1.21	4.99	.01	.00	.01	-.51	.00	4.50
2100	-1.89	4.83	.17	.00	.17	-.32	.00	4.85
2130	-1.22	4.88	.12	.00	.12	-.50	.00	4.62

In order to summarize the reasons, the results with large errors of three days are collected, and illustrated in Table 5 in order to investigate possible reasons.

Table 5.The collection of the results of three days with large errors using the data of LINEX-97/1 field study over the grassland on 16, 17 and 18 June 1997.

Time (UTC)	I %	II %	III %	IV %	V %	VI %	Total %	Reason Bo	Reason $\overline{w'T_s'}$
June 16, 1997									
0430	11.1	-6.1	-.1	-6.1	-56.2	-.3	-57.6	**-0.07**	**0.001**
1730	-14.3	19.4	.2	19.4	7.6	.0	32.4	**0.02**	**0.001**
June 17, 1997									
0430	4.9	.1	.0	.1	5.8	.0	10.9	**0.04**	-0.001
1730	4.7	.3	.0	.3	-9.8	-.0	-4.6	**-0.12**	-0.010
June 18, 1997									
0430	5.5	-.5	.0	-.5	18.1	.1	22.6	**-0.03**	0.007
1730	3.7	1.2	.0	1.3	21.7	.1	28.0	**-0.03**	-0.003

*) The black type indicates the reason of error

One of the reasons for large error is the contribution of the fifth term of Equation (8). During the three days, this condition only happened at the same time, 0430 (UTC) and 1730 (UTC). Obviously, they are caused by the values of the Bowen ratios that are in the above defined interval of –0.15 to 0.05. It can lead to large error when Equation (8) is used to obtain sensible heat flux. Therefore, the sensible heat flux, H_{MBR}, must be excluded when the Bowen ratio is between –0.15 and 0.05. On the other hand, during these periods, the sensible heat flux can be close to zero (positive or negative), which means that the stratification stability is changing, and the atmosphere is in non-steady state. Actually it doesn't satisfy one of the conditions of measurements of the near surface layer, stationarity. According to the similarity theory, the data should also be excluded. Therefore, this limitation can not be attributed to this method only, but to others as well.

Another large total errors, which are the contribution of the first four terms in Equation (8), often occur when $\left|\overline{w'T_S'}\right|$ is very small. As mentioned before, when $\left|\overline{w'T_S'}\right|$ is very small (e.g., $\left|\overline{w'T_S'}\right|$<<0.05), the measurement error of $\overline{w'T_S'}$ itself increases and can be up to 100%; therefore the error of the first term increases nearly up to ±100%. Even if the measurement error of $\overline{w'T_S'}$ can be taken as ±5% in this case, it can produce large error. For example, from Table 3, when $\overline{w'T_S'}$=0.001 in 0400 (UTC) and 1730 (UTC) on 16 June, it can make the values of $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$ equal to 0.45 and -0.82, and make $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$ equal to –0.35 and 0.26 respectively. Although these conditions occur at 0430 (UTC) and 1730 (UTC) in this study, they can appear in other periods when $\overline{w'T_S'}$ is very small. Therefore the fluxes with the $\overline{w'T_S'}$ values at least between –0.001 and 0.002 K·m/s should be excluded. Notice that the absolute error of $\overline{w'T_S'}$ is very small in this case.

The results from both the numerical experiment and the data calculation imply that the error of H_{MBR} could be from $\pm 5\%$ to $\pm 10\%$. Few large errors are excluded by the criteria given above. From Equation (9), it can be seen that the error of λE_{MBR} is simply the linear sum of the errors of Bo and H_{MBR} without any non-linear relationship. Based on the field experimental study, the error of Bo may be around $\pm 10\%$ as mentioned before; therefore, the error of λE_{MBR} may be considered to be less than $\pm 20\%$.

As expected, for a CSAT3 sonic anemometer, the factors A and B will appear in the denominators of the first four term of right hand side in Equation (8) in the form of $1+\frac{2\cdot\overline{T}}{\overline{c^2}}\cdot\frac{(\overline{u}\cdot\overline{w'u'}\cdot A+\overline{v}\cdot\overline{w'v'}\cdot B)}{\overline{w'T_S'}}$ and $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}\cdot\frac{1}{A}+\frac{\overline{v}\cdot\overline{w'v'}}{\overline{u}\cdot\overline{w'u'}}\cdot\frac{B}{A}$. However, the denominator $1+\frac{\lambda\cdot Bo}{0.51\cdot\overline{T}\cdot c_p}$ is same, thus the criterion for the Bowen ratio is still suitable when CSAT3 sonic anemometers are used. From the calculations, the factors A and B are equal and are 0.875 (Liu and Foken, 1999).

When $\overline{w'T_S'}$ <0.0 (i.e., <-0.05K·m/s), the factor $1+\frac{2\cdot\overline{T}}{\overline{c^2}}\cdot\frac{(\overline{u}\cdot\overline{w'u'}\cdot A+\overline{v}\cdot\overline{w'v'}\cdot B)}{\overline{w'T_S'}}$ is a little less than the factor $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$, but still greater than 1, the error of the first term is nearly equal to the measurement error of $\overline{w'T_S'}$. The factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}\cdot\frac{1}{A}+\frac{\overline{v}\cdot\overline{w'v'}}{\overline{u}\cdot\overline{w'u'}}\cdot\frac{B}{A}$ is a little greater that the factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$, and much greater than 1; therefore the sum of the error of the second, third and fourth terms is too small to be ignored.

When $\overline{w'T_S'}$ >0.0 (i.e., >0.05K·m/s), the factor $1+\frac{2\cdot\overline{T}}{\overline{c^2}}\cdot\frac{(\overline{u}\cdot\overline{w'u'}\cdot A+\overline{v}\cdot\overline{w'v'}\cdot B)}{\overline{w'T_S'}}$ is a little greater than the factor $1+2\cdot\frac{\overline{T}\cdot\overline{u}}{\overline{c^2}}\cdot\frac{\overline{w'u'}}{\overline{w'T_S'}}$, but less than 1 and close to 1. The error of the first term is little greater than the measurement error of $\overline{w'T_S'}$, but can be considered to be equal. The factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}\cdot\frac{1}{A}+\frac{\overline{v}\cdot\overline{w'v'}}{\overline{u}\cdot\overline{w'u'}}\cdot\frac{B}{A}$ is much less than –1, and its magnitude is greater than the magnitude of the factor $1+\frac{\overline{c^2}}{2\cdot\overline{T}\cdot\overline{u}}\cdot\frac{\overline{w'T_S'}}{\overline{w'u'}}$. The sum of the error of the second, third and fourth terms is too small to be ignored.

The results show that when $\overline{w'T_S'}$ is around zero, the large errors can occur, and the criteria that the flux with the $\overline{w'T_S'}$ values at least between –0.001 and 0.002 K·m/s should be excluded is suitable when CSAT3 sonic anemometers are used.

b. Error comparison between BREB of MBR

Many researchers have discussed the error analysis of Bowen ratio / Energy balance method. (e. g. Fuchs and Tanner, 1970; Ohmura, 1982; Wicke and Bernhofer, 1996; Foken et al., 1997b). Only the brief comparisons of error analysis between the two methods are referred to here. The error of fluxes obtained by Bowen ratio/Energy balance method can be rewritten as follows. (e. g. Wicke and Bernhofer, 1996; Foken et al., 1997b).

$$\frac{\delta H_{BREB}}{H_{BREB}} = \frac{1}{(1+Bo)} \cdot \frac{\delta Bo}{Bo} + \frac{\delta(R_n - G)}{(R_n - G)} + \frac{Re}{(R_n - G)} \tag{10}$$

$$\frac{\delta \lambda E_{BREB}}{\lambda E_{BREB}} = \frac{Bo}{(1+Bo)} \cdot \frac{\delta Bo}{Bo} + \frac{\delta(R_n - G)}{(R_n - G)} + \frac{Re}{(R_n - G)} \tag{11}$$

The difference is that the contribution of the error of the residuum of non-closure of the surface energy is considered in the equation. From Eqs. (10), (11), It can be seen that the errors of H_{BREB} and λE_{BREB} are caused by the measurement errors of Bowen ratio and available energy, and the residuum of non-closure of the surface energy balance.

In order to compare the errors of two methods only caused by Bowen ratio, only the first terms on the right-hand sides of Equation (10) and Equation (11) are discussed firstly as Equation (12) and Equation (13).

$$\frac{\delta H_{BREB}}{H_{BREB}} = \frac{1}{1+Bo} \cdot \frac{\delta Bo}{Bo} \tag{12}$$

$$\frac{\delta \lambda E_{BREB}}{\lambda E_{BREB}} = \frac{Bo}{1+Bo} \cdot \frac{\delta Bo}{Bo} \tag{13}$$

Figure 6 and Figure 7 illustrate the results of Equation (12) and Equation (13). It indicates that the relative errors of the latent heat flux by BREB increase nonlinearly with the decrease of Bowen ratio when Bowen ratios are less than zero.

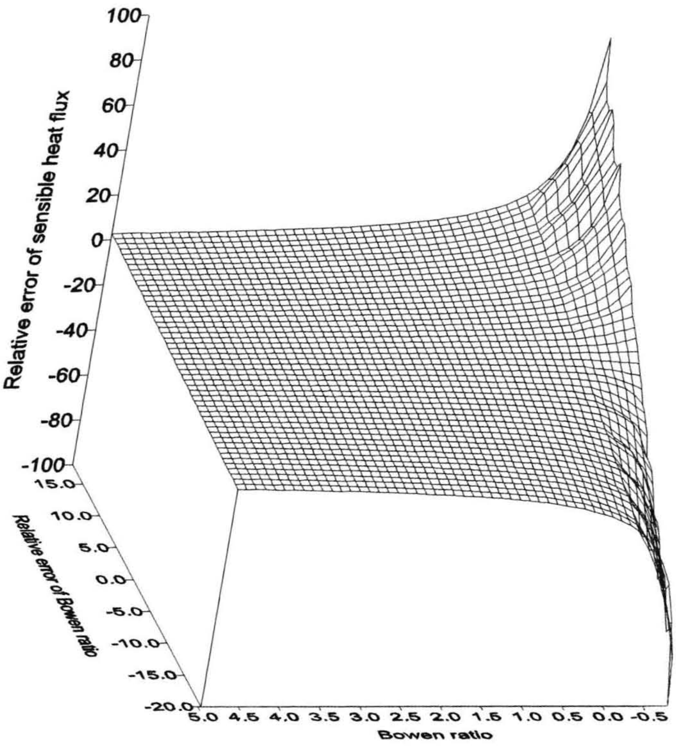

Fig. 6. Relative error of H_{BREB} by Equation (11)

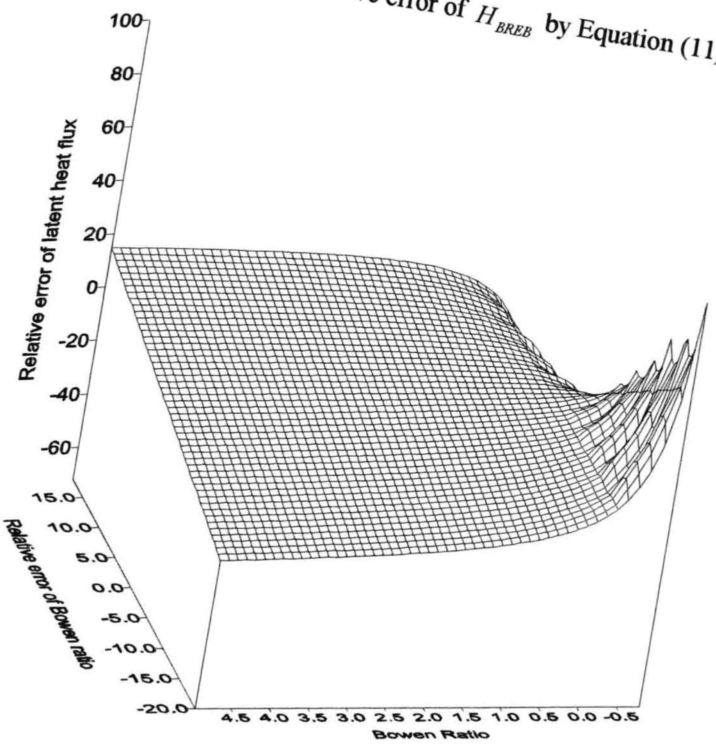

Fig. 7. Relative error of λE_{BREB} by Equation (12)

Table 6 shows some examples of the errors of $\frac{\delta H_{BREB}}{H_{BREB}}$ and $\frac{\delta\lambda E_{BREB}}{\lambda E_{BREB}}$ with $\frac{\delta Bo}{Bo}=$ ±10% from Figure 6 and Figure 7 with ignoring $\frac{\delta(R_n-G)}{(R_n-G)}$ (±10%) and $\frac{Re}{(R_n-G)}$ (25%).

Table 6. The examples of the errors of H_{BREB} and λE_{BREB} with ignoring the errors of ($R_n - G$) and Re when $\frac{\delta Bo}{Bo} = \pm 10\%$.

Bo	1.0	0.8	0.6	0.4	0.2	-0.1	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8
$\frac{\delta H_{BREB}}{H_{BREB}}$ (±%)	5.0	5.6	6.3	7.2	8.3	11.1	14.3	16.7	20.0	25.0	33.4	50.0
$\frac{\delta\lambda E_{BREB}}{\lambda E_{BREB}}$ (±%)	5.0	4.4	3.8	2.9	1.7	1.1	4.3	6.7	10.0	15.0	23.4	40.0

Obviously, when Bo >0.0, if ignoring the error caused by the residuum of the surface energy balance, $\frac{Re}{(R_n-G)}$ (20-30%), the fluxes by the BREB can be accepted with errors less than ±20%. When Bo<0.0, especially close to −1, the BREB can cause unacceptable errors, sometimes up to ±100%. This means that the BREB can not be used occasionally in hours of early morning, late afternoon, during precipitation and under the oasis effects, when the direction of the latent heat flux is opposite that of the sensible heat flux (Ohmura, 1982). Spittlehouse and Black (1980) have also found that for negative Bowen ratio, e. g. night-time and advection situations, there is a large relative error in the evapotranspiration rate.

In Equation (10) and Equation (11), the second term and third term indicate the measurement error of the available energy and the error caused by the non-closure error of the surface energy balance equation. Some results show that available energy (R_n- G) measurement should be accurate to better than ±10%. (Cellier and Olioso, 1993; Spittlehouse and Black, 1980; Barr, et al., 1994). If the non-closure of the surface energy balance is considered, the ratios of the residuum of non-closure of the surface energy to the available energy are usually in the order of 20-30% (Liu and Foken, 1999). This error will be distributed into sensible heat flux and latent heat flux according to Bowen ratio when the BREB is used to obtain sensible and latent heat fluxes. Therefore, even if available energy (R_n- G) measurement would be accurate to better than ±10%, it would also cause large errors because the BREB uses the unclosed surface energy balance equation especially with ignoring the heat storage in the soil and with the non-stationary conditions of the underlying surface (Kukharets et al., 1998).

On the contrary, from the above results, the error of H_{MBR} could be from $\pm 5\%$ to $\pm 10\%$ with few large errors excluded by the above criteria. The error of λE_{MBR} is simply the linear sum of the errors of B_o and H_{MBR} without any non-linear relationship, and may be considered to be less than $\pm 20\%$.

6. Conclusion

From the results of LINEX-97/1 field experiment, the BREB has errors of up to 35% for the sensible heat flux and 55% for the latent heat flux, which is mainly caused by the unclosed surface energy balance. The results and the error analysis show that the buoyancy flux measured with a sonic anemometer can be accepted after considering humidity and velocity transformations with errors of less than ±10%, and the latent heat flux can be obtained with errors of less than ±20%.

It is obvious that the MBR can obtain sensible and latent heat fluxes with better quality than the BREB. Particularly, the MBR can works well when Bowen ratio approaches −1, making Ohmura's criterion unnecessary.

However, the measured data and error analysis show that the following criteria must be used when MBR is used to obtain fluxes.

However, the following criteria must be used when the MBR is used to obtain fluxes.

(1). The fluxes must be excluded when $u_* < 0.07$ m/s because of poorly developed turbulent conditions.

(2). The fluxes whose Bowen ratio is between −0.15 and 0.05, and the fluxes with the $\overline{w'T_S'}$ values at least between −0.001 and 0.002 K·m/s should be excluded because of theoretical limitations of the MBR.

(3). Because of the fact that $\overline{w'T_S'}$ is directly determined by the eddy correlation method the sign λE_{MBR} of can be early determined according to Equation (6) even if $Bo<0$.

Acknowledgement

I am very grateful to Deutscher Wetterdienst, Meteorologisches Observatoriun Lindenberg for providing us the data of LINEX-97/1 experiment. I really appreciate Professor Dr. Thomas Foken for his many helpful discussions and comments, especially the contributions to this work. Many thanks are due to A. Mangold and M. Hierteis for their great help in processing the data of LITFASS-1998 experiment. I acknowledge the exchange programme between University of Bayreuth and Peking University, especially Dr. Heinz Pöhlmann for his great efforts on this programme.

REFERENCES

Barr, A. G., K. M. King, T. J. Gillespie, G. Den Hartog and H. H. Neumann, 1994: A comparison of Bowen ratio and eddy correlation sensible and latent heat flux measurements above deciduous forest. *Bound.-Layer Meteor.*, **71**, 21-41.

Bernhofer, Ch., 1992: Estimating forest evapotranspiration at a non-ideal site. *Agric. For. Meteor.*, **60**, 17-32.

Bowen, I. S., 1926. The ratio of heat losses by conduction and evaporation from any water surface. *Phys. Rev.* **27**, 779-787.

Cellier P., and A. Olioso, 1993: A simple system for automated long-term Bowen ratio measurement. *Agric. For. Meteor.*, **66**, 81-92.

Dugas, W. A., 1993: Micrometeorological and chamber measurements of CO2 flux from bare soil. *Agric. For. Meteor.*, **67**, 115-128.

Dugas, W. A., L. J. Fritschen, L. W. Gay, A. A. Held, A. D. Matthias, D. C. Reicosky, P. Steduto and J. L. Steiner, 1991: Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat. *Agric. For. Meteor.*, **56**, 12-20.

Foken, Th., 1998a: Die scheinbar ungeschlossene Energiebilanz am Erdboden - eine Herausforderung an die Experimentelle Meteorologie. Sitzungberichte der Leibniz-Sozietät, Berlin, in press.

Foken, Th. (Ed.), 1998b: Ergebnisse des the LINEX-97/1 Experimentes. *Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Arbeitsergebnisse* No. 53, 38pp.*)

Foken, Th., 1999: Energieaustauschmessungen über Brache. *Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Arbeitsergebnisse.* In press.

Foken, Th., and S. Oncley, 1995: Results of the workshop 'Instrumental and Methodical Problems of Land Surface Flux Measurements'. *Bull. Am. Meteorol. Soc.,* **76**, 1191-1193.

Foken, Th., and B. Wichura, 1996: Tools for quality assessment of surface-based flux measurements. *Agric. For. Meteor.,* **78**, 83-105.

Foken, Th., O. O. Jegede, U. Weisensee, S. H. Richter, D. Handorf, U. Görsdorf, G. Vogel, U. Schubert, H. J. Kirtzel and V. Thiermann, 1997a: Results of the LINEX-96/2 experiment. *Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Arbeitsergebnisse* Nr. 48, 75pp.*)

Foken, Th., S. H. Richter and H. Müller, 1997b: Zur Genauigkeit der Bowen Ratio Methode, *Wetter und Leben*, **49,** 57-77.

Foken, Th., A. L. Buck, R. A. Nye and R. D. Horn, 1998: A Lyman-alpha hygrometer with variable pathlength. *J. Atmos. and Ocean Tech.,* **15**, 211-214.

Fuchs, M., and C. B. Tanner, 1970: Error analysis of Bowen ratios measured by differential psychrometry. *Agric. Meteor.,* 7, 329-334.

Gay, L. W., R. Vogt, Ch. Bernhofer and J. H. Blanford, 1996: Flux agreement above a scots pine plantation. *Theor. Appl. Climatol.,* **53**, 33-48.

Hanafusa, T., T. Fujitani, Y. Kobiri and Y. Misuta, 1982: A new type sonic anemometer-thermometer for field operation. *Pap. Meteorol. Geophys.,* **33**, 1-19.

Kaimal, J. C., and J. A. Businger, 1963: A continuous wave sonic anemometer-thermometer. *J. Appl. Meteor.,* **2,** 156-164.

Kaimal, J. C., and J. E. Gaynor, 1991: Another look at sonic thermometry. *Bound.-Layer Meteor.,* **56**, 401-410.

Kukharets, V. P., V. G. Perepelkin, L. R. Tsvang, S. H. Richter, U. Weisensee and Th. Foken, 1998: Energiebilanz an der Oberfläche und Wärmespeicherung im Boden. In: Foken, Th., 1998b: Ergebnisse des LINEX-97/1 experimentes, 19-26.

Lindroth, A., and S. Halldin, 1990: Gradient measurements with fixed and reversing temperature and humidity sensors above a thin forest. *Agric. For. Meteor.,* **53**, 81-103.

Liu, Heping and Th. Foken, 1999a: A modified Bowen ratio method to determine sensible and latent heat fluxes. To be submitted to *J. Appl. Meteor.*

Liu, Heping, and Th. Foken, 1999b: New equations for omnidirectional sonic temperature variance and buoyancy heat flux with a sonic anemometer. To be submitted to *Bound.-Layer Meteor.*

Moncrieff, J. B., J. M. Massheder, H. de Bruin, J. Elbers, T. Friborg, B. Heusinkveld, P. Kabat, S. Scott, H. Soegaard and A. Verhoef, 1997: A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. *J. Hydrology*, **188-189**, 589-611.

Nie, D., I. D. Flitcroft and E. T. Kanemasu, 1992: Performance of Bowen ratio system on a slop. *Agric. For. Meteor.*, **59**, 165-181.

Ohmura, A., 1982: Objective criteria for rejecting data for Bowen ratio flux calculation. *J. Appl. Meteor.*, **21**, 595-598.

Panin, G. N., G. Tetzlaff, A. Raabe, H-J. Schönfeld and A. E. Nasonov, 1996: Inhomogeneity of the land surface and the parameterization of surface fluxes–discussion. *Wiss. Mitt. Inst. Meteorol. Univ. Leipzig and Inst. Troposphärenforschung Leipzig* **4**, 204-215.

Philipona, R., C. Fröhlich and Ch. Betz, 1995: Characterization of pyrgeometers and the accuracy of atmospheric long-wave radiation measurements. *Appl. Optics,* **34**, 1598-1605.

Schotanus, P., F. T. M. Nieuwstadt and H. A. R. DeBruin, 1983: Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. *Bound.-Layer Meteor.*, **26**, 81-93.

Spittlehouse, D. L., and T. A. Black, 1980: Evaluation of the Bowen ratio/energy balance method for determining forest evaporation. *Atmosphere-Ocean.*, **18**, 98-116.

Wick, W., and Ch. Bernhofer, 1996: Energy balance comparison of the Hartheim forest and adjacent grassland site during the HartX experiment. *Theor. Appl. Climatol.,* **53.** 49-58.

*Available from Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Postfach 100465, D-63004 Offenbach, Germany

Arbeitsergebnisse,
Universität Bayreuth, Abteilung Mikrometeorologie

Bislang erschienene bzw. vorgesehene Arbeiten:

Nr	Name	Titel	Seiten	Datum
01	Foken	Der Bayreuther Turbulenz-knecht	16	02/99
02	Foken	Methode zur Bestimmung der trockenen Deposition von Bor	13	02/99
03	Foken et al.	Nachtfrostgefährdung des ÖBG		03/99
04	Liu	Error analysis of the modified Bowen ratio method	23	02/99

Die Reihe dient dem Zweck einer schnellen fachlichen Dokumentation und Präsentation. Die Beiträge können in deutscher, englischer und russischer Sprache abgefaßt sein. Eine spätere Veröffentlichung soll hiermit nicht vorweggenommen werden. Für den Inhalt sind die Autoren selbst verantwortlich. Der englische Text der vorliegenden Arbeit wurde nicht sprachlich redigiert.

Die Reihe kann gegen eine Schutzgebühr bei der Abteilung Mikrometeorologie der Universität Bayreuth angefordert werden.Entwurf