Statistical Analysis and Comparative Study of Energy Balance Components Estimated Using Micrometeorological Techniques during HUBEX/IOP 1998/99

ZHU Zhilin* (朱治林), SUN Xiaomin (孙晓敏), and ZHANG Renhua (张仁华)

Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101

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ABSTRACT

In order to study energy and water cycles in the Huaihe River Basin, micrometeorological measurements were carried out in Shouxian County, Anhui Province, during HUBEX/IOP (May to August 1998 and June to July 1999). The employed techniques included Bowen Ratio-Energy Balance (BREB) and Eddy Covariance (EC) methods. In this paper, the basic characteristics of the energy balance components in the district are analyzed. Furthermore, the results are compared with those from other regions of China. The main results are as follows: (1) There was a consistency between the available energy ($R_n - G$) and the sum of sensible (H) and latent (E) heat fluxes measured by the EC method $(H+E)_{ec}$, but E_{br} was slightly larger (about 10%) than E_{ec}; (2) Most of the net radiation (R_n) was used to evaporate water from the surface. During HUBEX/IOP in 1998 and 1999, the mean daily amounts of R_n were 13.89 MJ m^{-2} d^{-1} and 11.83 MJ m^{-2} d^{-1}, and the mean Bowen Ratios (β) were 0.14 (over ruderal) and 0.06 (over paddy) respectively; (3) The diurnal variation characteristic of β was larger and unsteady at sunrise and sunset, and smaller and steady during the rest of the daytime. Local advection appeared in the afternoon over paddy areas in 1999; (4) In comparison with the results from other regions of China, the mean β was the lowest (0.06) over paddy areas in the Huaihe River Basin and the highest (0.57) during June–August 1998 in Inner Mongolia grassland. The Bowen Ratio β is mainly related to the soil humidity.

Key words: energy balance, micrometeorological method, Huaihe River basin, different surface

1. Introduction

The land surface is coupled with the atmosphere through the exchange of mass and energy. The surface-atmosphere interface process has become a critical component of various energy and water cycle models (Hurtalova and Matejka, 1999). Due to the differences of geographical location and surface conditions, the process and pattern of exchange are different too. Therefore, the radiation, energy, and water balances and their temporal and spatial distributions can be used to partly illustrate the ecological environment of a district. At present, how to measure or estimate the surface fluxes more accurately has become an important research field in micrometeorology. Many micrometeorological methods, such as the Bowen Ratio-Energy Balance (BREB) technique, Eddy Covariance (EC) technique, and Aerodynamic (AD) technique, are widely applied for estimating energy and water fluxes of surface-atmosphere (Garratt, 1984). For a long time, the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (IGSNRR, CAS), has paid attention to the research of energy and mass exchanges and has acquired advanced results (Chen et al., 1994; Wang et al., 1996; Zhu, 1991). Particularly, some high precision instruments have been developed, such as the Bowen Ratio observation system with a sensor-position automatic exchange mechanism, hot-wire anemometer, etc. (Sun et al., 1995).

The Huaihe River Basin plays an important role in the climate of China. The main purpose of HUBEX was to make clear the energy and water status and cycles in the district and their impacts on the climate of East China. In 1998 and 1999, large series of measurements, including some micrometeorological measurements (BREB and EC concerned observations), were executed during HUBEX/IOP. In this paper, based on

*E-mail: zhuzl@igsnrr.ac.cn

the data observed during HUBEX/IOP in 1998 and 1999, the authors analyze the basic characteristics of energy and vapor fluxes over two surfaces (ruderal and paddy) and compare the estimates of two methods. In addition, the results are compared with those obtained from other regions of China.

2. Theories and calculating methods

2.1 *Bowen Ratio-Energy Balance (BREB) method*

Based on the law of the conservation of energy and the gradient diffusion equation, surface energy balance can be expressed in the following equations:

$$R_{\mathrm{n}} = H + E + G\,, \tag{1}$$

$$H = \rho c_p K_{\mathrm{h}} \Delta t / \Delta z\,, \tag{2}$$

$$E = (1/\gamma) \rho c_p K_{\mathrm{w}} \Delta e / \Delta z\,, \tag{3}$$

where R_{n} is the net radiation, H and E are the sensible and latent heat fluxes, respectively, G is the soil heat flux, ρ is air density, c_p is the specific heat capacity of air, γ is the psychometric constant, K_{h} and K_{w} are the eddy diffusivities for heat and for water vapor, respectively, and $\Delta t, \Delta e$, and Δz are the gradients of temperature, vapor pressure, and height, respectively.

The Bowen Ratio (β) is defined as H/E. If we assume $K_{\mathrm{h}} = K_{\mathrm{w}}, \beta$ becomes

$$\beta = H/E = \gamma \Delta t / \Delta e\,. \tag{4}$$

Because R_{n} and G can be measured directly by a net radiometer and soil heat flux plate, respectively, H and E can be calculated by the following equations:

$$E = (R_{\mathrm{n}} - G)/(1+\beta)\,, \tag{5}$$

$$H = \beta (R_{\mathrm{n}} - G)/(1+\beta)\,. \tag{6}$$

2.2 *Eddy Covariance (EC) method*

Eddy Covariance theory was first presented by Swinbank, an Australian meteorologist, in 1951. With the development of computer and measuring techniques, it is at present known as one of the best techniques for measuring surface fluxes and its performance is regarded as the criterion for flux measurements (Chen, 1993). The Eddy Covariance method derivs the latent heat and sensible heat fluxes using the following relationships:

$$H = \rho c_p \overline{w'T'}\,, \tag{7}$$

$$E = \rho L \overline{w'q'}\,, \tag{8}$$

where w', T', and q' are the fluctuations of vertical wind velocity, temperature, and humidity, respectively. The overbar indicates time averaging. In the above equations, it has been assumed that the mean vertical wind velocity during a relatively long period, e.g., 10 minutes or longer, is zero.

3. Site, instrumentation, and observations

The 1998 measurements were conducted at the meteorological station of Shouxian County, Anhui Province (32°33′N, 116°47′E). The surface of the site was covered by ruderal; the surroundings near the site were bare soil or various vegetation types, and beyond was farmland. Therefore, the site was not very homogeneous. A house (observation room) was located approximately 80 m north of the site, and the other sides were open. The prevailing wind direction is south in the summer. The 1999 measurements were taken over a paddy located at about 2 km to the north of the 1998 site (Zhang et al., 2001).

The instruments of the BREB system included one net radiometer, manufactured by Jinzhou 322 Institute, China; two soil heat flux plates developed by China Agricultural University; and a Bowen Ratio measuring instrument with a sensor-position automatic exchange mechanism developed by IGSNRR, CAS. Air humidity was calculated based on dry-bulb and wet-bulb temperatures. Due to the use of the sensor-position auto-exchange technique, there is no systematic bias in the Δt and Δe measurements. The temperature sensors were made of platinum, with precisions of 0.03°C and 0.05°C in the laboratory and in the field, respectively. The temperature sensors were 0.5 m and 1.7 m above the ground, respectively. Two soil heat flux plates were buried at roughly 1 cm below the ground. The net radiometer was mounted 2 m above the ground. All data were collected by a data-logger (Datataker, DT100, Australia). The sampling interval was 15 s, and the interval of sensor-position exchange and exporting the averages was 5 min. For the 1999 experiment, net radiation was measured and calculated by a 4-way component method, and the temperature sensors were a little different too (Zhang et al., 2001). The observation periods were 1 May to 30 August 1998 and from 23 June to 22 July 1999.

The EC system consisted of a 1-D ultrasonic anemometer (model CA27, Campbell Scientific Inc., USA), a fine wire thermocouple (127, Campbell Scientific Inc., USA), and a Lyman-α hygrometer (BR, ERC Instrument Inc., USA). They were used for rapid measurements of vertical wind speed, temperature, and humidity, respectively. The system was installed near the BREB observation site. The heights of the sensors were 2 m above the ground. The data were collected by a high frequency data-logger (DASH-8, USA) with sampling frequency of 20 Hz per channel. The averaged durations were 10 min.

4. Results and discussions

4.1 *Comparison of fluxes from the EC and BREB approaches*

In the experiment, the EC method was regarded as an auxiliary measurement and was applied only to a portion of days in June and July 1998. The sum of sensible and latent heat fluxes $(H+E)_{ec}$ measured by the EC technique was compared with the available energy (R_n-G) in Fig. 1. Most points are scattered close to the 1:1 line. This implies that there was no systematic bias between the two measurements. Based on the part of data observed during the daytime (defined as the periods from 0600 LST to 1800 LST, hereafter) in 1998, the linear regression equation of the two measurements was

$$Y = 1.023X + 14.1 , \quad (9)$$

where Y is the sum of sensible and latent heat measured by EC $(H+E)_{ec}$, and X is the available energy (R_n-G). The regression coefficient is $r = 0.932$, and the number of samples is $n = 530$.

As a critical component of the energy and water balances, the latent heat fluxes estimated by the two techniques were compared as well. On the whole, as shown in Fig. 2, the latent heat flux estimated by BREB (E_{br}) was roughly 10% larger than that by EC (E_{ec}). The linear regression equation was

$$Y = 0.932X + 83.5 , \quad (10)$$

where X is E_{ec}, Y is E_{br}, $r = 0.881$, and $n = 530$.

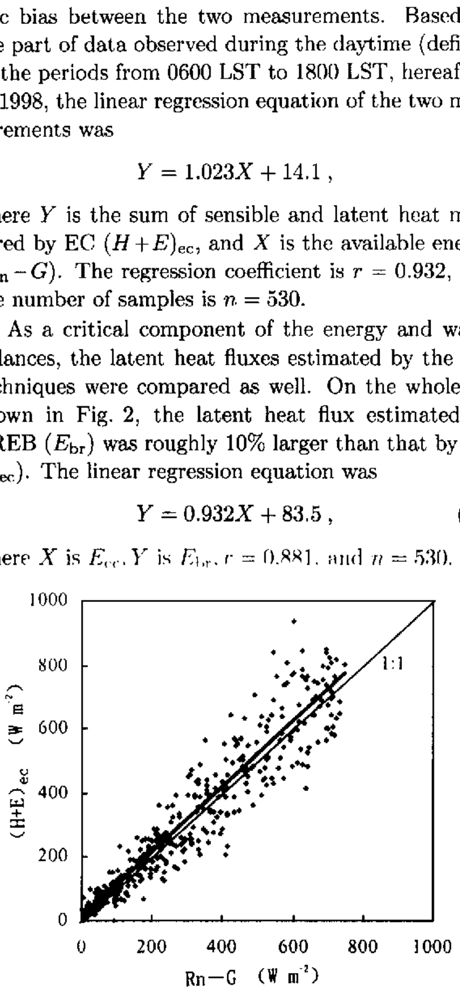


Fig. 1. Comparison of the sum of sensible and latent heat fluxes by the Eddy Covariance method $(H+E)_{ec}$ with the available energy (R_n-G), during HUBEX/IOP, 1998.

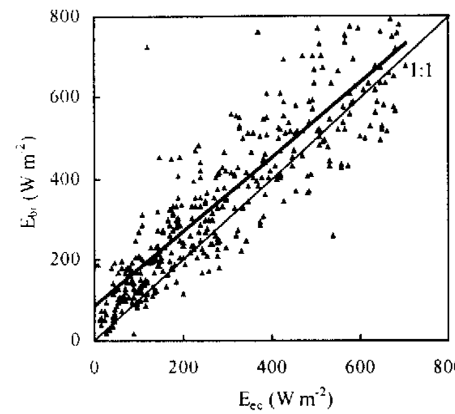


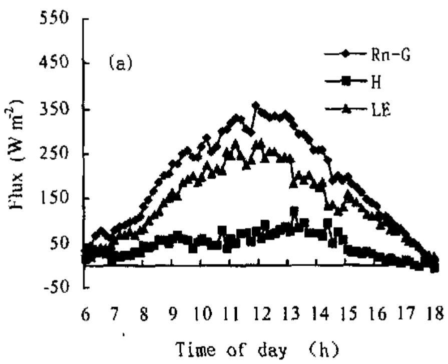
Fig. 2. Comparison of the latent heat flux estimated by the Eddy Covariance method (E_{ec}) with that estimated by the Bowen Ratio-Energy Balance method (E_{br}) during HUBEX/IOP, 1998.

The possible major causes of the difference between two estimations are given as follws. (1) The inhomogeneity of the observation site and surroundings. In general, the fetch of the homogeneous surface is at least 50–100 times longer than the height of the BREB instrument sensors (Blad and Rosenberg 1994; Angus and Watts 1984; Steduto and Hsiao, 1998). Otherwise, it may not meet the requirements for a constant flux layer. (2) The eddy diffusivity for heat may not equal the eddy diffusivity for a water vapor $(K_h \neq K_w)$. Verma et al. (1978) analysed the causes and concluded that the use of the equality assumption could result in a consistent underestimation of evapotranspiration. On the other hand, Lang et al. (1983) showed a case of $K_h < K_w$. (3) The precision of the instruments. Although the automatic sensor-position exchange mechanism can eliminate a systematic bias, random errors of the temperature sensors still exist (Sun et al., 1995). In addition, due to the neglect of the nonlinear output of the Lyman-α hygrometer, the errors of E measurements obtained by the EC method may have appeared; (4) The influence of weather conditions. Due to the changes of the atmospheric cycle and weather system, the wind speed, wind direction, and atmospheric stability also changes. Therefore, some obvious, existing data errors must be discriminated. On this issue, please see the literature (Zhu et al., 2001) in detail. Even so, the BREB technique is still reliable in most conditions and is applied widely at present.

4.2 *Diurnal changes of the energy balance components and the mean Bowen Ratio*

Figure 3 shows the mean pattern of the energy balance components during the daytime in May 1998 and in June–July 1999. As we know, R_n, or solar radiation, is the main energy source of sensible and latent heat flux exchanges. Whether the surface was ruderal or paddy, with the increasing of net radiation, as shown in Fig. 3, the sensible heat and latent and fluxes increase also, but the rate of increase of latent heat flux was much higher than that of sensible flux. This implies that most of the net radiation energy was consumed for evaporating water from surfaces. In May 1998, the soil of the site was relatively dry, so soil water content was a major limitation of evapotranspiration. In 1999, the paddy field was well irrigated, so almost all of the energy was transformed into latent heat flux. Particularly, the averaged sensible heat flux became negative in the afternoon, at approximately 1530 LST. This indicates that there may have been local advection over the paddy field.

Figure 4 presents the mean β diurnal variation in May and August 1998 and July 1999. Near sunrise or sunset was the time when the net radiation was changing from negative to positive, or vice versa. This means that the net radiation was close to zero, and H and E were very small as well. Therefore, β was very unsteady. This is the disadvantage of the BREB technique. In the daytime, the values of β were steadier than those near sunrise or sunset, and they displayed a decreasing trend. In particular, β became negative in 1999 because of local advection.



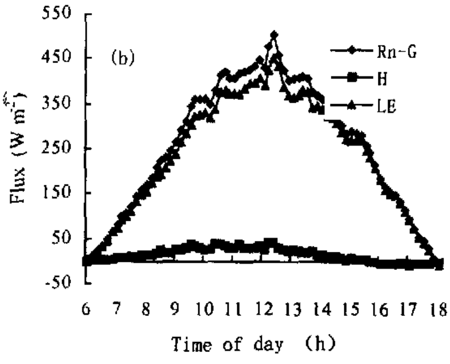


Fig. 3. Monthly-averaged diurnal changes of energy balance components during HUBEX/IOP. (a) May 1998, and (b) June–July 1999.

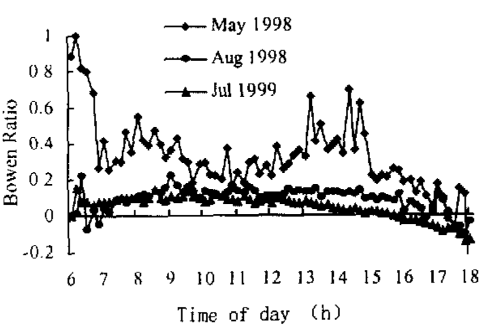


Fig. 4. Diurnal variations of the mean Bowen Ratio over different vegetations during HUBEX/ IOP, 1998/99.

Due to the effects of atmospheric stability, wind direction, wind speed, and weather system etc., the diurnal variations of energy fluxes and the Bowen Ratio in practice are more complex than shown above (Zhu et al., 2001).

4.3 *Seasonal changes of daily amounts of energy balance components and daily β*

In order to analyze the seasonal changes of the energy balance components, their daily amounts were calculated using integral method and are shown in Fig. 5, for the daytime in 1998 and 1999. Although there were some missing data during the study periods, the basic variation tendency can still be seen. The averages of daily amounts of R_n in May, June, July, and August 1998, and in June–July 1999 were 8.81 MJ m^{-2} d^{-1}, 14.34 MJ m^{-2} d^{-1}, 16.67 MJ m^{-2} d^{-1}, 15.72 MJ m^{-2} d^{-1}, and 11.83 MJ m^{-2} d^{-1} respectively. The averages of daily amounts of E in the same periods were 6.52 MJ m^{-2} d^{-1}, 12.09 MJ m^{-2} d^{-1}, 15.55 MJ m^{-2} d^{-1}, 13.99 MJ m^{-2} d^{-1}, and 10.88 MJ m^{-2} d^{-1}, respectively.

To some degree, the daily Bowen Ratio (defined as the ratio of the daily amount of H to the daily amount of E) can indirectly reflect the water status of a specific surface. In May and June 1998, because of the relatively dry surface, daily β was relatively large as shown in Fig. 5. In July and the early part of August 1998, daily β became relatively large again. In 1999, as the paddy field was always fully supplied with water, the mean daily β was the lowest. The averages of daily β in May, June, July, August 1988, and in June–

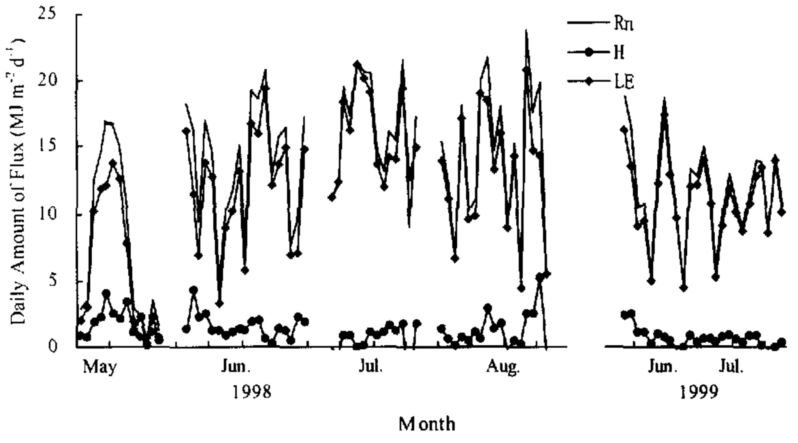


Fig. 5. The seasonal changes of daily amounts of energy balance components during HUBEX/IOP, 1998/99.

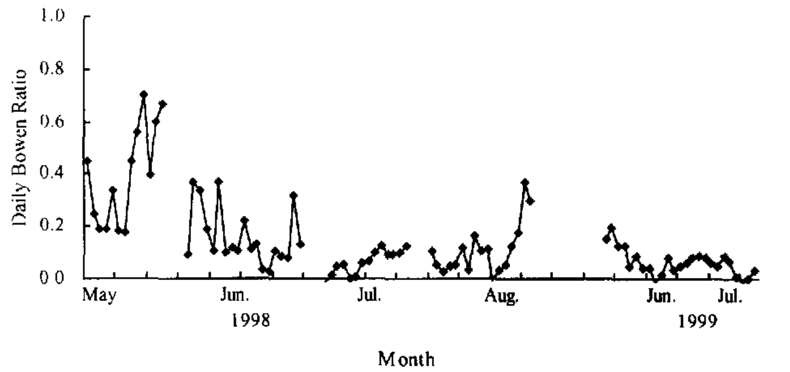


Fig. 6. The seasonal changes of daily Bowen Ratio during HUBEX/IOP, 1998/99.

July 1999 were 0.31, 0.15, 0.08, 0.11, and 0.06, respectively.

4.4 *Comparison of energy fluxes in different regions*

According to Eq.1, radiation energy (R_n) is transformed mainly into three kinds of energy patterns (H, E, and G). Their distributions vary according to various factors, such as soil water content, surface cover (vegetable or bare), and atmospheric conditions (Rosenberg et al., 1983).

In the last decade, similar experiments were executed over different surfaces and in different regions of China (Chen et al., 1994; Wang et al., 1996; Zhu et al., 1995). To show the contrast, Table 1 gives some main statistics there. The maximum and minimum daily-mean density of R_n were 372 W m^{-2} and 221 W m^{-2}, appearing over wheat fields in the Tibetan Plateau (because of less atmospheric attenuation for radiation transmission) (Wang et al., 1996) and in the North-China Plain, respectively. The Bowen Ratio is mainly relative to soil humidity over vegetable surfaces, as seen in the Table. The minimum mean β was 0.063 (paddy, in the Huaihe River Basin), and the maximum was 0.571 (pasture, in the Xilin Gol Grassland, Inner Mongolia Autonomous Region).

Because of the limitation of different observation periods and/or vegetation, in fact, the distributions of energy balance components in a specific region or over different vegetation types are very complicated. Even so, the statistics in Table 1 are still an effective reference for a general comparison.

Table 1. Daily-mean density of energy balance components during the daytime in different regions and over different surfaces

Region	Huaihe River Basin	Huaihe River Basin	Huaihe River Basin	Inner Mongolia Grassland	North China Plain*	Oasis in Gansu Province	Tibetan Plateau
Observation Period	May–Jun. 1998	Jul.–Aug. 1998	Jun.–Jul. 1999	May Aug. 1998	Mar.–May 1996	May 1992	Jun. 1994
Vegetation Cover	Ruderal	Ruderal	Rice	Pasture	Winter wheat	Spring wheat	Spring wheat
Soil Water Conditions	Moderate	Wet	Watery	Dry	Moderate	Irrigated	Moderate
R_n (W m^{-2})	268	334	274	354	221	345	372
G (W m^{-2})	9	6	6	21	17	21	27
H (W m^{-2})	44	26	16	121	42	51	71
E (W m^{-2})	216	302	252	212	162	273	275
β	0.204	0.086	0.063	0.571	0.26	0.186	0.258

*Data acquired from Yucheng Experimental Station, Chinese Academy of Sciences, located in Shandong Province.

5. Conclusions

Based on the analysis above, some major conclusions are given as follows:

(1) There is a consistency between the available energy ($R_n - G$) and the sum of sensible and latent heat fluxes measured by the Eddy Covariance method $(H+E)_{ec}$, but there were differences between the two latent heat fluxes: E_{br} was slightly larger (about 10%) than E_{ec}. The error sources are mainly related to the heterogeneous site, the equal diffusivity assumption, instruments, and weather.

(2) There are evident realtionships between latent heat flux and net radiation flux: most of the net radiation was used to evaporate water from the surface. In 1998 and 1999, the mean daily amounts of R_n were 13.89 MJ m^{-2} d^{-1} and 11.83 MJ m^{-2} d^{-1}; and mean β was 0.14 (ruderal) and 0.06 (paddy) during HUBEX/IOP, respectively.

(3) During the study periods, the diurnal variation characteristic of β was large and unsteady at sunrise and sunset, and smaller and steady during the rest of the daytime. In 1999, local advection appeared in the afternoon over the paddy areas. As for the seasonal variation of daily β, it was larger in May and late August, and smaller in June and July 1998.

(4) In comparison with the results observed in other regions of China, the mean β was the lowest (0.06) over the paddy areas in the Huaihe River Basin and was the largest (0.57) in the Xilingele Grassland, Inner Mongolia Autonomous Region.

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用微气象方法估算淮河流域能量平衡(HUBEX/IOP 1998/99)的统计分析和比较研究

朱治林 孙晓敏 张仁华

摘 要

利用1998和1999年HUBEX强化观测期在安徽寿县用微气象方法（波文比一能量平衡法和涡度相关法）观测的资料，分析了该地区的能量平衡特征，同时与其他地区的结果进行了初步比较，结果表明：（1）用涡度相关方法测定的感热和潜热之和$(H+E)_{ec}$与下垫面有效能量(R_n-G)的一致性比较好，但用波文比方法估算的潜热通量E_{br}比用涡度相关法测定的潜热通量E_{ec}略高(约10%)。(2)大部分净辐射能用于了地表蒸发，1998和1999年，净辐射通量的平均日总量分别是13.89 MJ m^{-2} d^{-1} 和11.83 MJ m^{-2} d^{-1}；两年的平均波文比分别是0.14 (杂草)和0.06 (稻田)。(3) 波文比在日出和日落时数值大且不稳定，白天比较小且比较稳定，另外，1999年在稻田上观测到明显的局地平流现象。(4) 通过与我国其他地区的观测资料比较，淮河流域稻田的波文比最小(0.06)，在内蒙古草原观测的波文比值最大(0.57)。波文比值的大小主要与土壤水分有关。

关键词：能量平衡，微气象方法，淮河流域，下垫面