Journal of Geographical Sciences 12, 3 (2002) 295–300 ISSN: 1009–637X

Variation of fluxes of water vapor, sensible heat and carbon dioxide above winter wheat and maize canopies

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Abstract: Surface energy fluxes were measured using Bowen-Ratio Energy Balance technique (BREB) and eddy correlation system at Luancheng of Hebei Province, on the North China Plain from 1999 to 2001. Average diurnal variation of surface energy fluxes and CO_2 flux for maize showed the inverse "U" type. The average peak fluxes did not appear at noon, but after noon. The average peak CO_2 flux was about 1.65 mg m^{-2} s^{-1}. Crop water use efficiency (WUE) increased quickly in the morning, stabilized after 10:00 and decreased quickly after 15:00 with no evident peak value. The ratio of latent heat flux (λE) to net solar radiation (R_n) was always higher than 70% during winter wheat and maize seasons. The seasonal average ratio of sensible heat flux (H) divided by R_n stayed at about 15% above the field surface; the seasonal average ratio of conductive heat flux (G) divided by R_n varied between 5% and 13%, and the average G/R_n from the wheat canopy was evidently higher than that from the maize canopy. The evaporative fraction (*EF*) is correlated to the Bowen ratio in a reverse function. *EF* for winter wheat increased quickly during that revival stage, after the stage, it gradually stabilized to 1.0, and fluctuated around 1.0. EF for maize also fluctuated around 1.0 before the later grain filling stage, and decreased after that stage.
Key words: latent heat flux; sensible heat flux; carbon dioxide flux; water use; North China Plain
CLC number: P332.2

Evapotranspiration (ET), as an important component of the terrestrial water cycle, represents more than 60% of precipitation inputs at the global scale (L'vovich and White, 1990). Through links between stomatal conductance, carbon exchange, and water use efficiency (WUE) in plant canopies (Woodward and Smith 1994; Sellers *et al.*, 1996), ET serves as a regulator of key ecosystem processes. Therefore, it is important to quantify the ET process, especially in arid or semi-arid areas where the water shortage prevents crops from growing normally. There are many methods to determine ET. Micrometeorological approaches, including the Bowen-Ratio Energy Balance (BREB) technique, aerodynamic method, eddy correlation method, etc, are popular methods, which have been developed to understand the process governing the transfer of energy and matter between the surface and atmosphere (Rana and Katerji, 2000). As a micrometeorological method, the BREB technique is often used to estimate latent heat flux (λE) because of its simplicity, mobility, and cost (Todd *et al.*, 2000). Eddy correlation technique can directly measure ET by the measurement of vertical wind fluctuations and vapor density at the same time. But its high cost often prohibits its application. We applied the two methods in ET measurement on a field scale in the North China Plain (NCP) where the water shortage is a se-

Received date: 2002-02-09 **Accepted date:** 2002-05-30
Foundation item: National Natural Science Foundation of China, No.40071008; No.49890330; Academician Agricultural Water-saving Foundation, Hebei Province of China, No. 01220703D; Special Fund for Major State Basic Research Project, No. CXIOG-C003-03
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rious constraint on crop production. The situation was aggravated in the 1990s by an increase in agricultural and industrial demand for groundwater. It has become fundamental to know the exact losses of water by crop ET in the area. Primary productivity of a given crop genotype depends on the accumulation over time of biomass through CO_2 assimilation (Steduto and Hsiao, 1998a; 1998b). CO_2 flux over a canopy is often measured by the eddy correlation technique. The ratio of λE to CO_2 flux is the crop WUE that is often used to evaluate the efficiency of crop water use at an instant time. Improvement of WUE in the NCP area was discussed (Yu *et al.*, 1992; Wang *et al.*, 2001). We used the eddy correlation technique to acquire crop *WUE* above maize canopy. The objective of the study was to quantify the process of energy and CO_2 flux and WUE.

1 Site description

Experiments were conducted at the Luancheng Agro-Ecosystem Station (37°53'N, 114°41'E, altitude 50.1 m), one of the 29 agri-ecosystem stations of the Chinese Ecological Research Network (CERN). The experimental site is located in a high-yield farming area of the NCP, with fertile, organic loam soil. The main crops are winter wheat and summer maize. Wheat is planted in early October, is dormant over the winter, revives in early spring, and is harvested in mid-June. Maize is planted in early June and harvested with mechanized equipment in late September. With its semi-arid monsoon climate, precipitation in the NCP mostly occurs from July to September. Mean annual precipitation, temperature and global radiation at the station over the past 20 years were 480.7 mm, 12.2 °C, and 524.2 kJ/cm^2, respectively. During the summer, precipitation is usually sufficient to meet the water demands of maize. However, drought often occurs during the winter wheat season, when the average ET rate of about 480 mm greatly exceeds the average precipitation rate of about 130 mm. The average annual crop reference ET and crop actual ET at the station were 1098.8 mm and 919.5 mm, respectively, from November 1995 to September 2000. Groundwater is used to meet the deficit water requirement for winter wheat, resulting in chronic water table declining beneath the NCP.

2 Experiments and calculations

2.1 Experiments

The experiments were carried out in 1998-2001. The observation items include Bowen ratio system measurements (net radiation [R_n], conductive heat flux [G], temperature, vapor pressure gradient, and wind speed) and the eddy correlation system including λE, sensible heat flux (H) and CO_2 flux.

A Bowen-ratio system (023A) manufactured by Campbell Scientific Inc. was installed about 1.0 m high above the crop canopy in the field. The ambient temperature gradient was measured with a pair of E type chromel-constantan thermocouples installed on two arms; vapor pressure measurements were made by air sampling through an inlet on each arm, at a rate of 0.41 min^{-1} for a 2-min period; net radiation was determined with a Q7-1 net radiometer, with hemispherical polyethylene windshield domes protecting the sensor surfaces; G was determined by using two HFT3 soil heat flux plates. All measurements were averaged at 20-min intervals, and all data were stored in a Campbell's CR10X data logger. The Bowen ratio system ran from December 1998 to September 2001.

An eddy correlation system was installed in the tower of Luancheng Station at a height of 8 meters above the canopy. The system is composed of a KH-20 hygrometer (Campbell Scientific Inc.), a CSAT3 three-dimension super-anemometer (Campbell Scientific Inc.) and a LI-7500 open CO_2/water vapor infrared analyzer (Li-Cor Scientific Inc.). The hygrometer directly measured λE; the anemometer directly measured H; the LI-7500 infrared analyzer measured λE and CO_2 flux at the same time. All data were stored in a Campbell's CR21X data logger at 30-min intervals. Unlike the Bowen-ratio system, the eddy correlation system ran from May 2001 to September 2001 because of its expensive value.

2.2 Bowen ratio–energy balance method

The energy balance equation above the crop canopy surface is as follows

$$R_n = \lambda E + H + G \tag{1}$$

where R_n is net radiation flux, G is conductive heat flux, λE is latent heat flux, and H is sensible heat flux; all units are in W m^{-2}. R_n and G can be measured directly through the instruments. The difference between R_n and G is usually called "available energy". λE and H are calculated as

$$\lambda E = \frac{\rho C_p}{\gamma} K_w \frac{\partial e}{\partial z} \tag{2}$$

$$H = \rho C_p K_h \frac{\partial T}{\partial z} \tag{3}$$

where λ is latent heat, ρ is air bulk density, C_p is air specific heat at a constant pressure, γ is the psychometric constant, K_w and K_h are diffusion coefficients of vapor and heat transfer, and are gradients of vapor pressure and air temperature, respectively. Given that K_w is equal to K_h, according to the similarity principle, we can then introduce the Bowen ratio, β, with

$$\beta = \frac{H}{\lambda E} \tag{4}$$

The components of energy partitioning, λE and H, could be deduced as

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{5}$$

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

The latent heat flux of the components of the energy balance can be obtained by analyzing the dimensionless evaporative fraction, EF, defined as

$$EF = \frac{\lambda E}{R_n - G} = \frac{1}{1 + \beta} \tag{7}$$

2.3 Eddy correlation technique

Latent heat flux, sensible heat flux and carbon dioxide flux can be expressed as follows:

$$H = \rho C_p \overline{w'T'} \tag{8}$$

$$\lambda E = \rho L \overline{w'q'} \tag{9}$$

$$F_{co_2} = - \overline{w'c'} \tag{10}$$

where H is sensible heat flux, λE is latent heat flux, F_{co_2} is carbon dioxide flux, C' is the fluctuation of gas density (mol/m^3), and w' is the vertical fluctuation of wind speed (m/s).

3 Results and analysis

3.1 Diurnal pattern of water, heat and carbon dioxide fluxes above the maize canopy

Figure 1 shows the diurnal pattern of λE, H, F_{co_2}, Bowen ratio and crop WUE on maize season of 2001. The data were averaged from DOY 210 to DOY 234 (2001/7/29-2001/8/22). The observation took place from the heading stage to the grain-filling stage, when the maize grows rapidly. The diurnal pattern of λE and H shows the inverse "U" type. The average peak λE appeared from 14:00 to 15:00, while the average peak of H occurred at 13:00. The average peak values of λE and H are 291.71 W/m^2 and 53.04 W/m^2, respectively (Figure 1a). The diurnal pattern of CO_2 flux showed an asymmetrical "U" type, and the peak value, about 1.65 mg m^{-2} s^{-1}, appeared between 14:00 to 15:00, similar to that of λE (Figure 1b). The diurnal

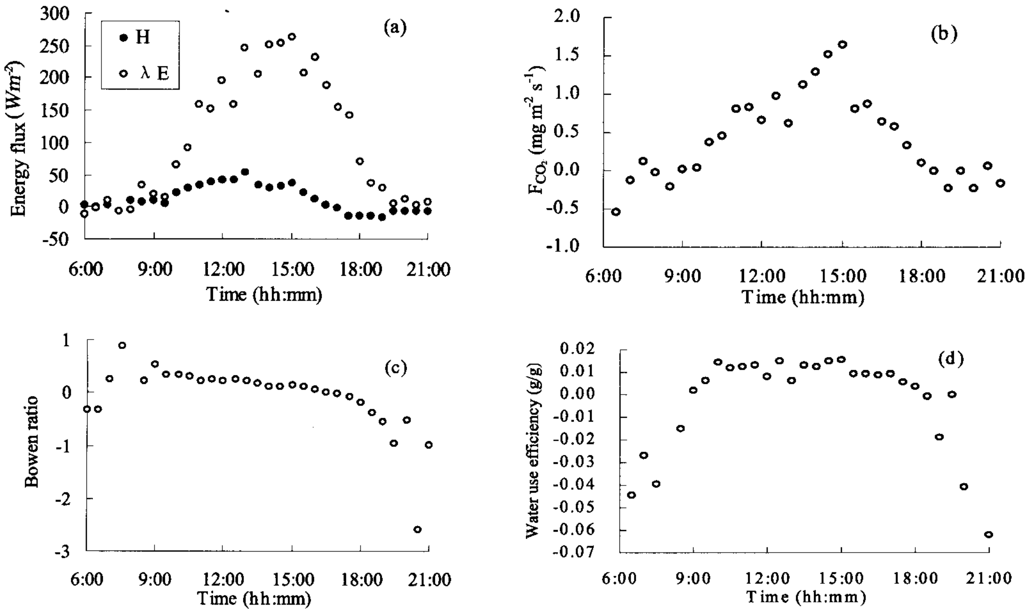

Figure 1 Diurnal patterns of latent heat flux (λE), sensible heat flux (H), CO_2 flux (F_{co_2}), Bowen ratio (β) and water use efficiency (WUE) above maize canopy (2001) (Average results by eddy correlation technique from 29 July to 22 August 2001)

pattern of the Bowen ratio showed that it increased quickly in the morning, then decreased slowly. The average peak Bowen ratio was about 0.9 (Figure 1c). The diurnal pattern of WUE increased from 6:00 to 10:00, stabilized from 10:00 to 15:00, then decreased after 15:00. The highest WUE was about 0.015 g/g without a clear value (Figure 1d). The diurnal change of WUE showed that carbon dioxide increased more quickly than λE from 6:00 o'clock *to* 10:00. They changed in a similar pattern from 10:00 to 15:00. λE decreased more quickly than CO_2 flux after 15:00.

3.2 Seasonal variation of energy fluxes above winter wheat and maize canopies

Figure 2 shows seasonal trends of the components of the surface energy balance above canopies of winter wheat and maize in 1999 and 2000. All fluxes in Figure 2 are midday averages of measurements taken every 20 minutes from 10:00 am to 3:00 pm. Energy fluxes of winter wheat are shown from the revival to the grain filling stage, and those of maize are shown from the stem extension to the grain filling stage. Midday fluxes on rainy days are not shown. Figure 2 shows that net radiation (R_n) and latent heat flux (λE) varied drastically, but exhibited similar seasonal trends. Sensible heat flux (H) and soil heat flux (G) were relatively small. All $\lambda E/R_n$ exceeded 70% during the four growing stages, and $\lambda E/R_n$ for maize slightly exceeded $\lambda E/R_n$ for winter wheat. H/R_n varied between 13% and 16%, and H/R_n for winter wheat was almost the same as for maize. G/R_n varied between 5% and 13%, and the average G/R_n for wheat exceeded G/R_n for maize. 5-7% of net radiation energy was used to transfer energy to the soil in the selected maize growth stages, compared to 10-13% in the selected winter wheat stages. The energy balance reveals that, following the stem extension growth stages of both winter wheat and maize, R_n was mainly used for crop evapotranspiration.

The Bowen ratio and EF averaged from 10:00 to 15:00 were calculated by equations (4) and (7), respectively. β for winter wheat varied from 0 to 2.0, with the maximum value occurring during the revival stage (Figure 3). After revival, β decreased quickly, then stabilized near zero. Seasonal average β values were 0.31 and 0.22 in 1999 and 2000,

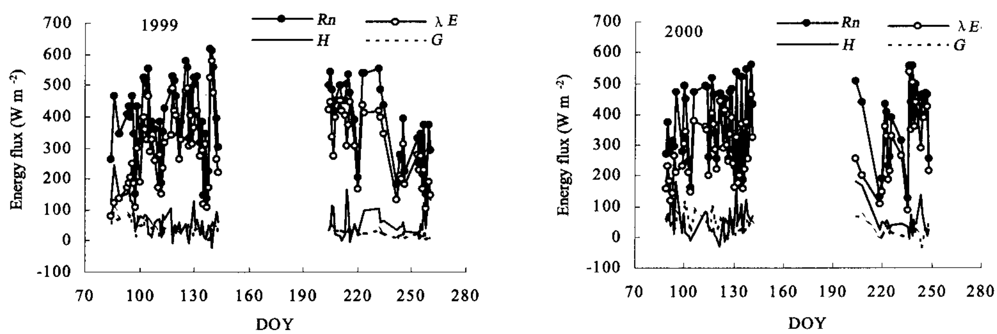

Figure 2 Mean midday (10:00 to 15:00) surface energy fluxes in 1999 and 2000. Net radiation flux (R_n), latent heat flux (λE), sensible heat flux (H) and soil heat flux (G) were measured by the BREB technique

respectively. β for maize varied more drastically than for winter wheat, showing no obvious seasonal trend before the grain filling stage in 1999, after which β ascended. No data are available for the grain filling stage in 2000, when the BREB system was removed. EF showed a reverse trend than of the Bowen ratio, because EF is inversely proportional to $1+\beta$. *EF* for winter wheat increased quickly during the revival stage; after that stage, it gradually stabilized to 1.0; and fluctuated around 1.0. *EF* fluctuation range of maize is wider than that of winter wheat, and EF for maize also fluctuated around 1.0 before the later grain filling stage, and decreased after that stage. This shows that available energy for wheat and maize was almost exclusively used for evapotranspiration in order to meet crops growing from the stem extension to the grain filling stage.

3.3 Comparison of the BREB technique and the eddy correlation system

As two micrometeorological methods, the BREB technique and the eddy correlation system are different in the principle of ET measurement. Based on energy balance and the similarity principle, the BREB technique estimates ET indirectly. According to the air turbulence principle, the eddy correlation system measures ET directly. The λE of the BREB technique was not completely consistent with that of the eddy correlation system (Figure 4). The square of the correlation coefficient of the two methods was only about 0.46. There are two possibly reasons that cause the discrepancy (Zhang et al., 2002). (1) The eddy correlation system was installed 8 m above the maize canopy, while the BREB technique was implemented 1 m above the maize canopy. There is a scaling problem because the BREB technique is different from the eddy correlation system in measurement fetch. (2) Sometimes, the λE of eddy correlation

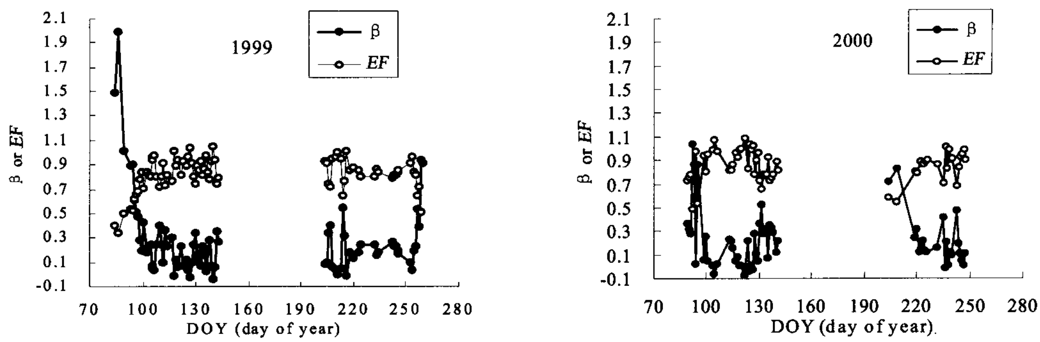

Figure 3 Seasonal pattern of Bowen ratio (β) and evaporation fraction (EF) in 1999 and 2000

system is lower than the actual λE. The slope of the relationship between the frequency and the power spectrum of water vapor density is steeper than - 2/3. Air sampling and sensor response may produce some of underestimation of λE (Ohta , 2001).

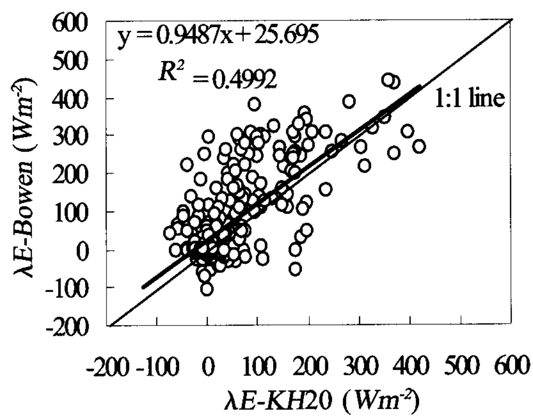

Figure 4 Comparison of latent heat flux (λE_KH20) of the eddy correlation system KH20 and that (λE_Bowen) of the BREB technique

4 Conclusion

(1)Average diurnal variation of surface energy and CO_2 flux for maize showed the inverse "U" type. The peak fluxes did not appear at noon, but after noon. Crop water use efficiency (WUE) increased quickly at morning, stabilized after 10:00 and decreased quickly after 15:00 with no evident peak value.

(2)$\lambda E/R_n$ was greater than 70% during the four observation seasons in 1999-2000. The seasonal average of H/R_n above the field surface was about 15%; the seasonal average of G/R_n varied between 5% and 13%, and the average G/R_n of the wheat canopy was significantly higher than of the maize canopy.

(3)The BREB technique was not completely consistent with the eddy correlation system in measuring the crop ET process.

Acknowledgement

We are grateful to Margii Crackel from Graduate School, the Chinese Academy of Sciences for her excellent assistance in editing the paper.

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