Energy balance closure at ChinaFLUX sites

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Abstract Network of eddy covariance observation is measuring long-term carbon and water fluxes in contrasting ecosystems and climates. As one important reference of independently evaluating scalar flux estimates from eddy covariance, energy balance closure is used widely in study of carbon and water fluxes. Energy balance closure in ChinaFLUX was evaluated by statistical regression of turbulent energy fluxes (sensible and latent heat) against available energy (net radiation, soil heat flux, canopy heat storage) and the energy balance ratio (EBR) and the frequency distribution of relative errors of energy balance (δ). The trends of diurnal and seasonal variation of energy balance in ChinaFLUX were analyzed. The results indicated that the imbalance was prevalent in all observation sites, but there were little differences among sites because of the properties variation of sites. The imbalance was greater during nocturnal periods than daytime and closure was improved with friction velocity intensifying. Generally the results suggested that estimates of the scalar turbulent fluxes of sensible and latent heat were underestimated and/or that available energy was overestimated. Finally, we discussed certain factors that are contributed to the imbalance of energy, such as systematic errors associated with the sampling mismatch, systematic instrument bias, neglected energy sinks, low and high frequency loss of turbulent fluxes and advection of heat and water vapor.

Keywords: energy balance, ChinaFLUX, eddy covariance technique.

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In recent years, eddy covariance technology was used widely in measuring carbon, water and energy exchange of net surface between terrestrial ecosystems and atmosphere. Now, there are some 271 eddy covariance observation sites distributing in the world. Measuring long-term carbon, water and energy exchange in many ecosystems provides a contribution to the study of global climate changing. With the increasing of flux sites, the research of net surface between biosphere and atmosphere will be more in-depth. On the other hand, how to evaluate the dependability of the flux data is becoming an important issue in flux study. Although the source-sink distributions for water, heat and CO_2 are different from each other in ecosystems, the atmospheric transport mechanisms within and above the canopy, which are measured by eddy covariance, are similar for all scalars and the computation of all scalar fluxes using the eddy covariance technique is founded on similar theoretical assumptions. According to the first law of thermodynamics and basic assumptions of eddy covariance, theoretically energy balance closure is capable to act as an effective method for evaluating the data quality and systematic observation capability. Energy balance closure requires that the sum of the estimated latent (*LE*) and sensible (*H*) heat flux be equivalent to the sum of net radiation (R_n), soil heat flux (*G*), canopy heat storage (*S*) and other energy sinks and sources. Energy balance closure has been widely accepted as an important reference of evaluating eddy covariance data[1,2], and a number of individual sites within the FLUXNET network served energy balance closure as a standard procedure to judgment of flux data quality[3,4].

Abroad, there are lots of studies on the issue of energy balance closure. McCaughey[5] and Moore[6] had shown that canopy heat storage had variable effects on the degree of energy balance closure with different vegetation heights. Schmid[7] provided a detailed discussion on sampling error because of the inability to match the source areas of three-dimension sonic anemometer and CO_2, H_2O infrared gas analyzer measurements (the flux footprint) with the source area of the instrumentation measuring R_n. Baldocchi[8] and Kustas[9] indicated that the imbalance of energy balance would generally be greater in open canopies or in canopies with large gradients where heterogeneity was present in biophysical characteristics. Mayocchi[10] and Verhoef[11] studied the possible measuring errors of soil heat flux when using soil heat flux plates. Moore[12] and Aubinet[13] suggested that the eddy covariance technique would underestimate turbulent fluxes sometimes because of low pass filter (high frequency loss) and high pass filter (low frequency loss). As to the effect of advection of heat and water vapor on energy balance, Stannard[14] suggested that terrain could affect the extent of closure, and found a larger lack of closure at sites across topographic variations where could promote local circulations and drainage flows. Sun[15] showed that even slight elevation gradients over a range of spatial scales could induce nocturnal drainage flows and advection near the surface during periods of strong static stability. Blanken[16] and Aubinet[13] proved that there was large mismatch in available energy and turbulent fluxes, when friction velocity was low. Lee[17] hypothesized that the lack of energy balance closure during nocturnal periods was often the result of mean vertical advection. A lot of work to find the reasons for imbalance of energy only aimed at one observation site, and few studies had synthetically evaluated the issue of energy balance at many observation sites. Wilson[18] anatomized and evaluated energy balance closure at FLUXNET from different points of view.

In China, the eddy covariance technology has been just applied in large-scale measuring material and energy exchange of different ecosystems[19]. Establishment of ChinaFLUX has provided a platform for the research of carbon, water and energy exchange between terrestrial ecosystems and atmosphere in China. Analyzing and evaluating energy balance closure is a pressing task for the study of ChinaFLUX, and also is an important issue of flux research worldwide. The major aim of this study is: to evaluate energy balance closure at all ChinaFLUX sites, to analyze the trends of diurnal variation and seasonal variation of energy balance, and to discuss the effect of friction velocity on energy balance closure. Based on these analyses, we can provide the references for evaluating flux data quality, ascertaining the methods of data analysis and improving research approaches.

1 Materials and methods

1.1 Description of sites

At present, ChinaFLUX consists of eight sites, which apply micrometeorological method, including four forest sites (Changbaishan, Qianyanzhou, Dinghushan, Xishuangbanna), three grassland sites (Haibei, Inner Mongolia, Dangxiong) and one cropland site (Yucheng). These sites are across the mainland of China and include a range of vegetation types and climates. The brief descriptions of sites are listed in table 1. More information is available on the website (http://www.chinaflux.org).

1.2 Dataset selection

Dataset of this study included flux data and routine meteorological data, the measured periods cov-

Table 1 Summary of the ChinaFLUX sites in this study[a)]

Site	Lon. (° E)	Lat. (° N)	Vegetation	Height/m	MAP/mm	MAT/℃	IRGA
CBS	128.0958	42.4025	DBCMF	41.5	750	−2.4	O/C
QYZ	115.0667	26.7333	MPF	23.6	1443	17.8	O/C
DHS	112.5333	23.1667	EBF	27	1956	20.9	O
XSBN	101.2000	21.9500	TSRF	48.8	1493	21.8	O
HB	101.3000	37.6000	Alpine meadow	2.2	600	−1.7	O
NMG	117.4500	43.5000	Grassland	2.2	350	−0.4	O
DX	91.0833	30.8500	Alpine meadow	2.2	477	1.3	O
YC	116.6000	36.9500	Cropland	2.2	528	13.1	O

a) O: Open path system; O/C: open/close path system; DBCMF: deciduous broad-leaved and coniferous mixed forest; MPF: man-planted forest; EBF: evergreen broad-leaved forest; TSRF: tropical seasonal rainforest.

ered one year for Changbaishan (CBS), Qianyanzhou (QYZ), Dinghushan (DHS), Xishuangbanna (XSBN), Haibei (HB) and YuCheng (YC). The dataset also included the data of Inner Mongolia (NMG), and Dangxiong (DX), and that measured periods only covered eight months because the two sites were established in the year 2003.

1.3 Data processing

In order to eliminate the items of horizontal and vertical advection in the equation of conservation of mass[13], the raw 30 min flux data were reformed by three–dimension coordinate rotation that aligned the vertical velocity measurement normal to mean wind streamlines and brought the mean lateral and vertical velocity to zeros. The effect of fluctuation in air density on the flux data also was corrected[20]. After above corrections, the irrational data was also deleted: (1) precipitation occurred at the same time; (2) records were incomplete during 30 minutes period, and (3) $|F_{NEE}| > 3.0$ mg $CO_2 m^{-2} s^{-1}$, which meant flux data was abnormal. According to effect of turbulent mixing on flux data quality, the data uncertainty could be lowed or reduced under high friction velocity ($u*$)[21]. Based on former studies, the friction velocity threshold was 0.1 m s^{-1} in this study, that is, only flux data with friction velocity higher than 0.1 m s^{-1} can be filtered out in analysis. Because the calculations of energy balance closure related to R_n, G and S, turbulent fluxes data and routine meteorological data should be recorded at the same time. The finally filtered dataset consisted of 9239, 4403, 12916, 11383, 3673, 7835, 6732 and 8219 records in DHS, XSBN, CBS, HB, DX, NMG, QYZ and YC, respectively.

1.4 Data analysis

According to the first law of thermodynamics, energy is neither produced nor dissipated, and only transfers from one form to another, and energy balance closure can be written as

$$LE + H = R_n - G - S - Q, \qquad (1)$$

where R_n is the net radiation, G soil heat flux, S canopy heat storage, and Q the sum of all additional energy sources and sinks. Typically, Q is neglected as a small term.

Energy balance closure at ChinaFLUX sites was evaluated using four different methods. The first and second methods were to derive linear regression coefficients (slope and intercept) from OLS (the ordinary least squares) and RMA (Reduced Major Axis) relationships between the half-hourly estimates of the dependent turbulent flux variables against the independently derived available energy. OLS method differs RMA from their fundamental hypothesis. OLS hypothesizes that the E_{OLS} is minimum, however, RMA hypothesizes that the E_{RMA} is minimum.

$$E_{OLS} = \sum[(x_i - X_i)^2 + (y_i - Y_i)^2], \qquad (2)$$

$$E_{RMA} = \sum(x_i - X_i)(y_i - Y_i), \qquad (3)$$

where x_i, y_i are x-coordinate and y-coordinate of datum point, X_i, Y_i are x-coordinate and y-coordinate of the point on the line of regression that is the nearest to the datum point. Ideal closure is represented by an intercept of zero and slope of 1.

The third method of evaluating degree of energy balance closure is energy balance ratio (EBR), which is a ratio of turbulent heat flux of eddy covariance to available energy.

$$\mathrm{EBR} = \left[\sum(LE+H)\right] / \sum[R_n - G - S]. \quad (4)$$

Frequency distribution of relative error of energy balance (δ) serves as another method of evaluating degree of energy balance closure. The relative error of energy balance (δ) is a ratio of the residual in the energy imbalance to available energy.

$$\delta = [(R_n - G - S) - (LE + H)] / [R_n - G - S]. \quad (5)$$

If δ value is more than zero, it means that turbulent energy fluxes (sensible and latent heat) measured by eddy covariance system are lower than available energy measured by routine meteorological. Otherwise, the result is opposite.

The above-mentioned R_n, G were measured directly by net radiometer (CNR-1, Kipp & Zonnen) and two soil heat flux plates, respectively; LE and H were measured by eddy covariance system (CSAT-3, Campbell Scientific Inc and IRGA, Li7500, LICOR Inc). McCaughey[5] and Moore[6] suggested that canopy heat storage had a great effect on degree of energy balance closure when the vegetation height was more than 8 m. In this study, canopy heat storage was calculated at four forest sites, excluded grassland and cropland sites. Canopy heat storage can be written as

$$S = S_a + S_\lambda + S_{\mathrm{leaves}} + S_{\mathrm{trunks}}, \quad (6)$$

$$S_a = \frac{\partial}{\partial t}\int_0^{hc} \rho C_p (1 + 0.84\bar{q}) T_b \mathrm{d}_Z, \quad (7)$$

$$S_\lambda = \frac{\partial}{\partial t}\int_0^{hc} \rho \lambda q_b T_b \mathrm{d}_Z, \quad (8)$$

where S is canopy heat storage, S_a sensible heat storage in the canopy air, S_λ latent heat storage flux through change in moisture content of the canopy air, S_{leaves} heat storage in the canopy leaves, S_{trunks} heat storage in the canopy trunks, hc · the height of the canopy, ρ air density, C_p specific heat of air, $\bar{q}$ mean specific humidity within canopy air and T_b temperature in the canopy air, q_b the specific humidity of the canopy air.

However, in this study, the item of S_{leaves} and S_{trunks} was not taken into account for evaluation of canopy heat storage because of the lack of biomass temperature of leaves and trunks. The results suggested that including S in the regressions for forest sites increased the slope of the OLS regression by an average of 6.6%. Soil heat flux (G) increased the average OLS slope for grasslands and cropland sites by about 8%. Soil heat flux had much less impact at the forested sites, where the average OLS slope increased by about 3%.

2 Results

2.1 Linear regression analysis of energy balance with OLS, RMA and energy balance ratio

The ideal energy balance closure would be achieved when the slope of linear regression is 1 with the intercept of zero. To represent the relative degree of energy balance closure, the slope of a linear regression, S_1, and the slope of a linear regression forced through the origin, S_2 are used. This is necessary because the linear relationship between turbulent energy fluxes and available energy usually produces a significant intercept. Regression coefficients of turbulent energy fluxes against available energy, using OLS on all the half-hour data at eight sites, are shown in table 2.

Regression coefficients of $LE+H$ against R_n–G–S are shown in table 2. The S_1 ranged from 0.49 to 0.81, with a mean of 0.67. The intercept ranged from 10.8 to 79.9 $\mathrm{Wm^{-2}}$, with a mean of 28.9 $\mathrm{Wm^{-2}}$. The mean coefficient of determination (R_1^2) was 0.82, ranging from 0.52 to 0.94. The S_2 ranged from 0.54 to 0.88, with a mean of 0.73. The mean coefficient of determination (R_2^2) was 0.77, ranging from 0.51 to 0.93.

The OLS regression is technically valid only if there are no random errors in the independent variable[22], which would incorrectly imply that the measurements of R_n, G and S contain no random errors. In order to eliminate effects of random error, the reduced major axis (RMA) method was used to analyze degree

Table 2 Ordinary linear regression coefficients and energy balance ratio at ChinaFLUX sites[a)]

Site	n	S_1/S_2	Intercept	R_1^2/R_2^2	EBR
CBS	12916	0.71/0.73	10.8	0.89/0.89	0.83
QYZ	6732	0.72/0.76	16.9	0.88/0.88	0.77
DHS	9239	0.70/0.74	24.4	0.77/0.76	0.82
XSBN	4403	0.49/0.54	22.5	0.52/0.51	0.58
HB	11383	0.70/0.77	40.4	0.93/0.90	0.91
NMG	7835	0.70/0.73	13.7	0.94/0.93	0.83
DX	3673	0.53/0.70	79.8	0.75/0.52	0.90
YC	8219	0.81/0.88	23.2	0.89/0.78	1.00

a) R_1^2 and R_2^2 are coefficients of determination. EBR is energy balance ratio.

of energy balance closure (not shown). Using the RMA approach, which accounted for random errors in available energy, increased the mean S_1 to 0.72. The increase in S_1 ranged from 1.5 to 9.6%. The mean intercept using the RMA method was slightly less than using the OLS method. But the RMA approach had lower correlation (R^2 mean value was 0.75) than using the OLS method. When using energy balance ratio (EBR) represented degree of energy balance closure, imbalance was still existent. The mean annual EBR was 0.83, ranging from 0.58 to 1.00.

The degree of energy balance closure was different among sites because of the properties (topography, vegetation and geographical location) variations of sites. According to the linear regression coefficients and EBR, the degree of energy balance closure at XSBN site was low; that at DX, NMG, DHS, HB, CBS, QYZ was better than at XSBN and the YC site was best, its S_1 was 0.81 and S_2 was 0.88, and annual EBR was 1.00.

2.2 Frequency distribution of relative errors of energy balance (δ)

To characterize energy balance closure in detail, 30 min δ data in daytime (global radiation >1 Wm^{-2}) were separated into 20 groups, according to 0.1 intervals between two groups. We firstly numerated the number of δ records in each group, then computed its frequency respectively and drew out the figure of δ frequency distribution (figs. 1 and 2). By the δ frequency distribution, we could know how many turbulent energy fluxes and available energy are in accord, and how many records are in different groups. The modeling normal distribution curves (dashed lines in figs.1 and 2) were based on the mean δ of four forest sites and the mean δ of grassland and cropland sites, respectively. The real lines were normal distribution curves, which possessed of the same standard deviation (σ) with modeling curves and their expectation were zero (μ =0). At forest sites, on average, there were 46% observational data in the extent of positive and negative standard deviation ($\pm\sigma$); CBS, DHS, QYZ and XSBN were 51%, 47%, 56% and 29%, respectively. In the extent of double positive and negative standard deviation ($\pm2\sigma$), there were 81% observational data on average; CBS, DHS, QYZ and XSBN were 83%, 80%, 84% and 75%, respectively. At grassland and cropland sites, on average there were 55% observational data in the extent of positive and negative standard deviation ($\pm\sigma$); HB, DX, NMG and YC were 63%, 36%, 64% and 59%, respectively. In the extent of double positive and negative standard deviation ($\pm2\sigma$), there were 78% observational data on average; HB, DX, NMG and YC were 89%, 72%, 83% and 76%.

At the ideal conditions, given definite standard deviation (σ), the δ distribution of eddy covariance data should be similar with normal distribution curves of real lines. But figs.1 and 2 show that the modeling curves (dashed lines) deviate from the ideal normal distribution curves. At the forest sites, the modeling curve deviate 3.6 intervals to right, and the modeling curve of grassland and cropland sites deviate 2.6 intervals to right, which indicate that imbalance of energy is not controlled by the random factors, but dominated by the systemic errors of eddy covariance and routine meteorological observation systems. Assumed available energy, measured by routine mete-

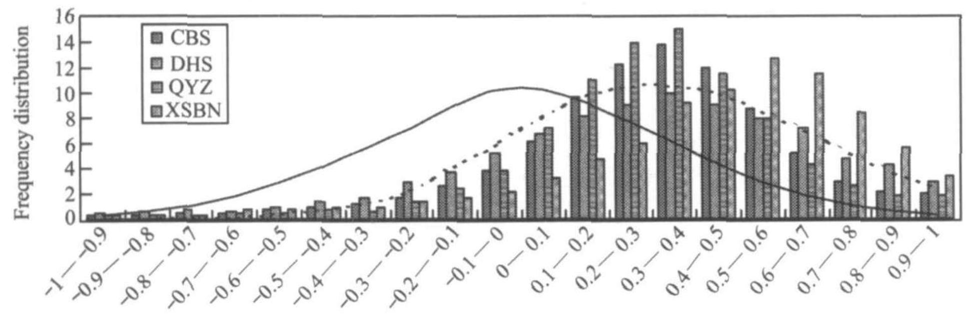

Fig. 1. Frequency distribution of relative errors of energy balance (δ) at forest sites.

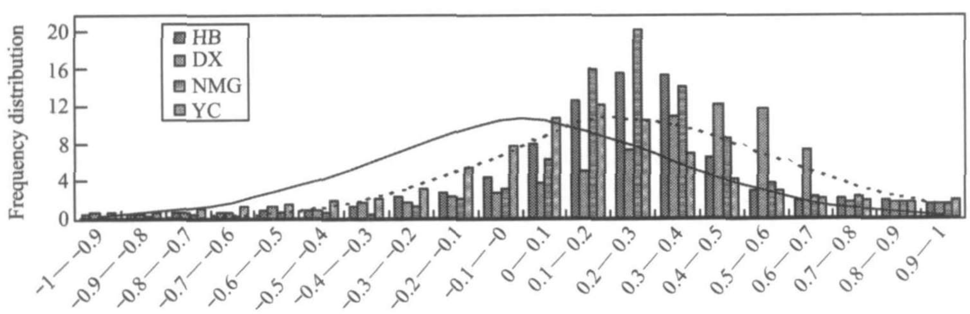

Fig. 2. Frequency distribution of relative errors of energy balance (δ) at grassland and cropland sites.

orological systems, is true, we might consider that turbulent energy fluxes are underestimated by eddy covariance system. But we cannot assure whether the assumption is correct. The reasons for the deviation require further study.

2.3 Diurnal variation of energy balance

The degree of energy balance closure during daytimes (global radiation >1 Wm^{-2}) differed greatly contrasting to that during nighttime (table 3). Forced through the origin, the OLS regression statistics during daytimes were similar to those using all the data that are shown in table 2. The mean slope (S_{day}) was 0.72, ranging from 0.54 to 0.86 and R^2_{day} was 0.75. The mean EBR_{day} of eight sites during daytime was 0.75, ranging from 0.57 to 0.95. The mean OLS slope (S_{night}) during nighttime was only 0.39, ranging from 0.18 to 0.54 and the correlation was typically weak (the mean R^2_{night} value was 0.30). The most of nocturnal EBR_{night} was small, and in two cases EBR_{night} was negative. The mean EBR_{night} was 0.31 during nighttime, which was less than during daytime. According to the OLS slope and EBR (shown in table 3), the closure degree during nighttime was lower than during daytime. The magnitude of the imbalance at night was strongly dependent on turbulent mixing, as shown in the following section.

The data were sorted into 48 groups by observational time to analyze diurnal variation in closure. For each of 48 groups, the half-hourly $LE + H$ and R_n–G–S were summed and the half-hourly EBR was calculated. The hourly EBR was the mean of two half-hourly EBR. Fig. 3 shows the diurnal course of the EBR, along with the mean magnitudes of $LE +H$ and R_n–G–S. During morning and evening transition periods, when the mean value of R_n–G–S is close to zero, the EBR drastically change. Between these two transition periods there is a general increase in the EBR from the morning to afternoon. This pattern of a greater EBR in the afternoon relative to the morning was observed in both the warm and cold seasons[18].

2.4 Seasonal variation of energy balance

At three forest sites (CBS, QYZ, XSBN), grassland (HB) and cropland (YC) sites, the turbulent energy fluxes data had good continuity during the whole year. Turbulent energy fluxes and available energy

Table 3 Ordinary linear regression coefficients and energy balance ratio at ChinaFLUX sites during daytime and nocturnal periods[a)]

Site	S_{night}	R^2_{night}	EBR_{night}	S_{day}	R^2_{day}	EBR_{day}
CBS	0.47	0.26	0.43	0.73	0.82	0.73
QYZ	0.54	0.50	0.43	0.76	0.84	0.71
DHS	0.53	0.45	0.40	0.74	0.61	0.72
XSBN	0.18	0.04	-0.01	0.54	0.47	0.57
HB	0.41	0.48	0.37	0.78	0.85	0.80
NMG	0.38	0.24	0.49	0.73	0.92	0.75
DX	0.24	0.18	-0.10	0.63	0.65	0.74
YC	0.38	0.28	0.54	0.86	0.80	0.95

a) S_{night} and S_{day} are the slope of OLS regression, forced through the origin.

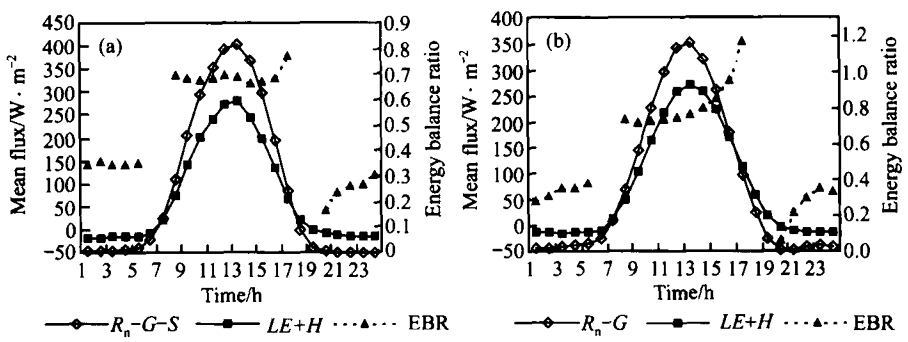

Fig. 3. The mean diurnal energy balance ratio. Also shown are the mean diurnal values of $LE + H$ and R_n–G–S. Forest sites (a), grassland and cropland sites (b).

were accumulated by month, and then the monthly EBR was calculated at those sites respectively. The seasonal variation of energy balance ratio is shown in fig. 4. The EBR increased continuously from winter to summer. The degree of energy balance closure in winter was very low, and was better in summer, their monthly EBR was almost 1 at most sites. The interesting phenomenon was that the EBR of forest sites was much lower than 1 in winter, which meant that turbulent energy fluxes were underestimated, however, the EBR of grassland and cropland sites was higher than 1 in winter, which meant that turbulent energy fluxes were higher than available energy. When we added DX and NMG sites in analysis, the phenomenon that turbulent energy fluxes were overestimated became more obvious. Limited by the number of sites, we cannot assure whether the phenomenon (in winter, turbulent energy fluxes were underestimated at forest sites and were overestimated at grassland and cropland sites.) is true. The real reasons need further observations and researches.

CBS, YC, and HB sites had sufficient data within all months of the year to analyze the variations of energy balance ratio of DOY. Fig. 5 shows that most of daily EBR at CBS, YC, and HB sites slightly fluctuate near 1 value in warm seasons, but their variation trends of daily EBR show different shapes. At CBS forest site, a large number of daily EBR in winter is lower than 1, however much daily EBR of YC cropland site and almost all daily EBR of HB grassland site are higher than 1. According to the trends of variation of energy balance ratio of DOY, the phenomenon also was shown that turbulent energy fluxes were underestimated at forest sites and were overestimated at grassland and cropland sites in winter. The reason for the phenomenon might be explained as follows: In winter, the long-wavelength radiation of earth at forest sites is lessening, which leads to net radiation increasing so that EBR value decreases accordingly. But, at grassland and cropland sites, the ground is exposed because vegetation has perished and been decomposed in winter and sometimes covered by a mass of snow. So the ground reflectivity during these periods is much higher than that in warm seasons. The net radiation gets less by reason of high ground reflectivity and EBR value often higher than 1.

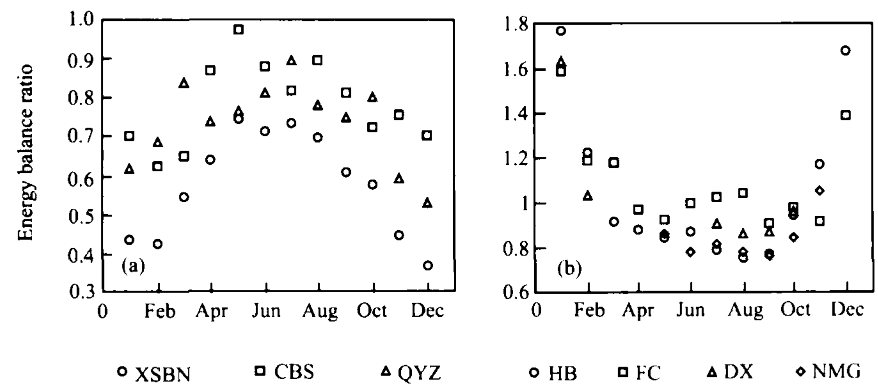

Fig. 4. The seasonal variation of energy balance ratio. (a) Forest sites, (b) grass and cropland sites.

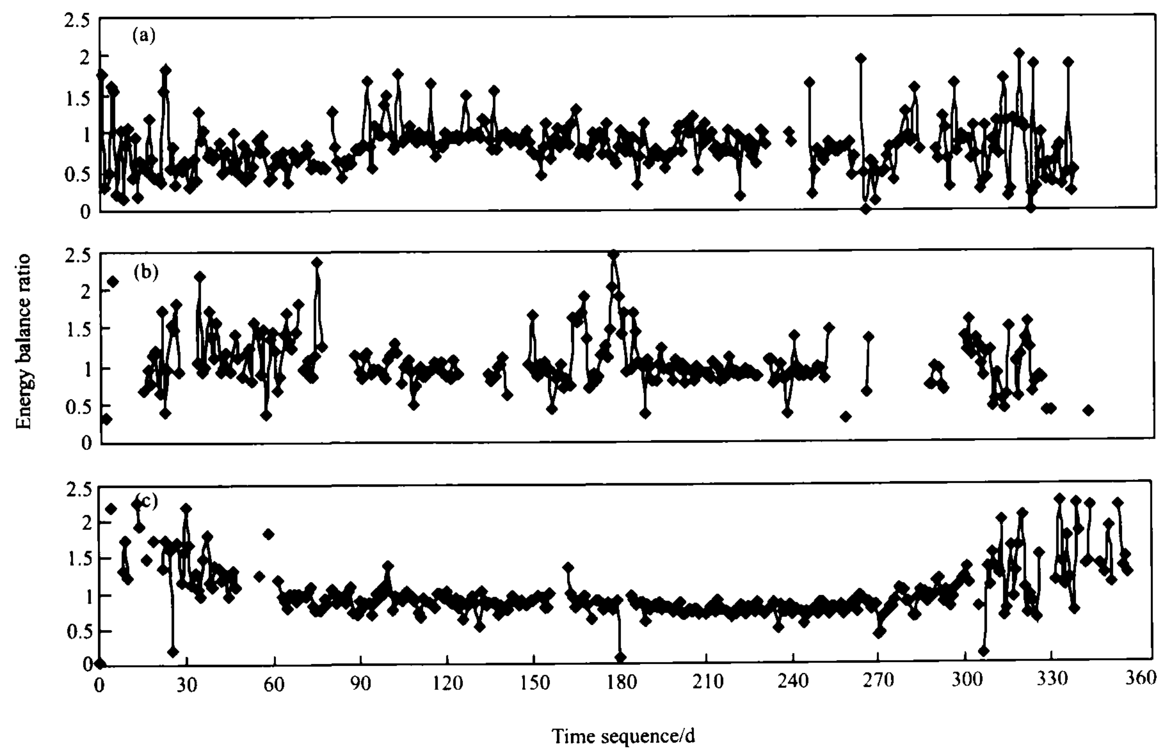

Fig. 5. Variation of energy balance ratio of DOY: (a) CBS site; (b) YC site; (c) HB sites.

2.5 Effect of turbulent mixing

Concerning the relationships between friction velocity and energy balance closure, this study discussed the effect of turbulent mixing on energy balance closure. All data were separated into daytime and nighttime groups, according to whether global radiation value was higher than 1 Wm^{-2}. For both daytime (global radiation >1 Wm^{-2}) and nighttime (global radiation >1 Wm^{-2}), data from each group were segregated by friction velocity into five percentile groups (five sets, each with 20% of total data). There was a very weak trend for the OLS slope to increase with friction velocity during daytime. However, during nocturnal periods, the OLS slope was smaller but was more dependent on friction velocity (fig. 6). When the mean friction velocity was below 0.5 ms^{-1}, the slope of the OLS regression during nocturnal periods increased rapidly with friction velocity. But if the mean friction velocity exceeded 0.50 ms^{-1}, the slope only slightly increased, and gradually became constant. The detailed relationships between friction velocity and energy balance closure are shown in fig. 7.

At three forest sites, the slope of the OLS regression increases rapidly with friction velocity when the mean friction velocity is below 0.5 ms^{-1}, and when the mean friction velocity is exceeded 0.5 ms^{-1}, the slope only slightly increases; moreover the slope almost increases no more at CBS sites (fig. 7(a)). At HB, NMG and YC sites, the relationships between friction velocity and OLS slope are similar to those at forest sites. The increasing trend of their OLS slopes (excluding NMG site) becomes weak when the mean friction velocity exceeds 0.5 ms^{-1} (fig. 7(b)).

3 Discussions

At ChinaFLUX sites, the S_1 of the OLS regression ranged from 0.49 to 0.81, with a mean of 0.67. The S_2 of the OLS regression ranged from 0.54 to 0.88, with a mean of 0.73. The mean annual EBR was 0.83, ranging from 0.58 to 1.00. In the extent of double positive and negative standard deviation ($\pm 2\sigma$) of δ frequency distribution, on average, there were 81% observational data at forest sites and 78% observational data at grassland and cropland sites. The seasonal variation of energy balance showed that the EBR was almost 1 in warm seasons. The degree of energy balance closure was very low in winter, maybe because of melting, freezing which were not considered in energy balance evaluation. In the diurnal variation of energy balance, the degree of energy balance closure had a great difference between daytime and nighttime. Generally, the lack of full energy balance closure at ChinaFLUX sites was consistent with EuroFLUX, AmeriFLUX and AsiaFLUX. Assumed available energy was true, we might consider that turbulent energy fluxes were underestimated by eddy covariance system. Based on previous studies, expla-

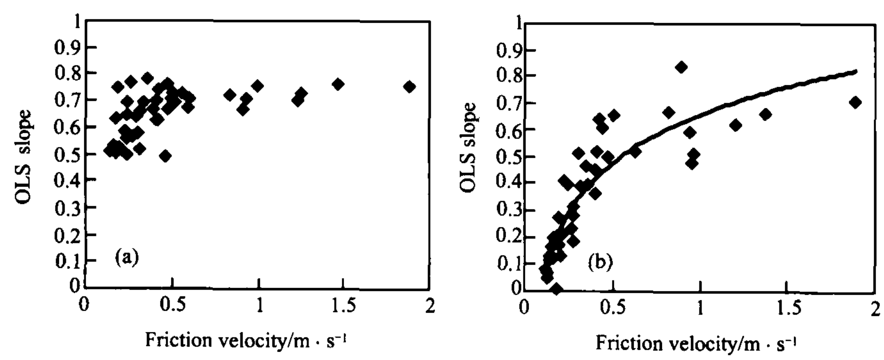

Fig. 6. The OLS slope against friction velocity (u^*). (a) During daytime periods; (b) during nocturnal periods.

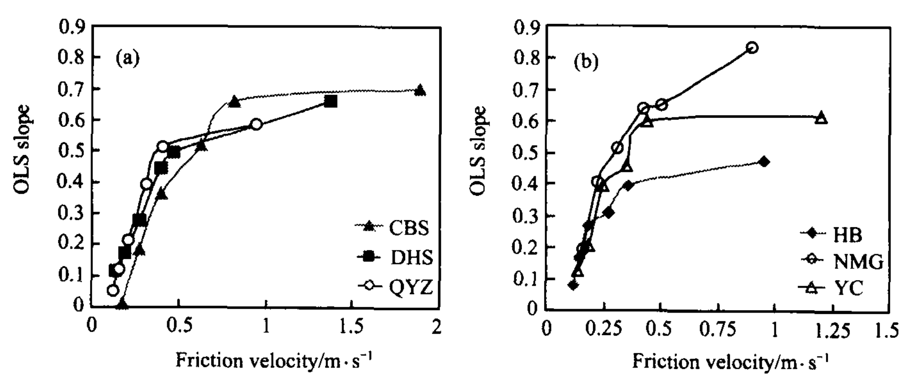

Fig. 7. The OLS slope against friction velocity (u^*) during nocturnal periods. (a) Forest sites; (b) grassland and cropland sites.

nations for the imbalance of energy can generally be summarized as follows:

(1) Systemic sampling errors in flux observations. The sampling error is associated with the inability to match the source areas of the eddy covariance measurements (the flux footprint) with the source area of the instrumentation measuring R_n, G and S. The source area for a net radiometer has a radius related to sensor height that is centered below the instrument and is fairly constant with time and wind. Alternatively, the spatial dimension of the flux footprint is not fixed in space and is dependent on atmospheric conditions, typically approximating an ellipse that is distorted in the mean upwind direction. In theory and practice, the source areas for a net radiometer and eddy covariance flux footprint never match. This systematic error would generally be greater in open canopies or in canopies with large gradients in biophysical characteristics, where heterogeneity is present at multiple scales[8,9]. The assumption of equivalent source areas is even more problematic when relating soil heat flux (G) to R_n, H and LE. The soil heat flux plates are several orders of magnitude smaller than the associated source areas of the net radiometers and the eddy covariance flux footprint. A similar daunting problem exists for the estimation of canopy heat storage in tall vegetation.

(2) Systematic instrument bias. Inaccurate calibrations of instruments and data processing errors can affect energy balance closure. Cross calibration of instrumentation and right processing of data collectors have probably reduced research uncertainties of energy balance closure[13,23]. Systematic instrument bias occurred mainly because the instruments had not been accurately calibrated in time. Several studies have addressed the accuracy of various brands of net radiometers and the accuracy of different calibration methods of one net radiometer[24−26]. With regard to soil heat flux plate, when its thermal conductivity is not equal to surrounding soil on specific conditions, it can be inaccurate[10,11]. Instrument errors can also occur with the eddy covariance instrumentation: Latent (LE) and sensible (H) heat flux are calculated by using velocities and temperature of sonic anemometer and water vapor of IRGA. Mounting equipment and instrumentation may shadow sonic anemometers and degrade data quality and energy balance closure in certain wind directions.

(3) Neglect of other energy sinks. An assumption in the analysis of energy balance closure is that the energy in the system can be approximated from the five measured components (LE, H, R_n, G, and S). Even if each of the five components is accurately measured, the imbalance of energy is still occurring because energy balance system also includes additional energy sinks (Q), such as the soil heat storage above soil heat flux plate, the vegetation heat storage of canopy heat storage, the biochemical energy storage transformed by photosynthesis and the energy transforming in the meteorological process of melting, freezing and sublimating, and so on. In this study, these energy sinks (Q) were not considered, which might bring some errors in available energy calculation.

(4) Low and high frequency loss of turbulent fluxes. The eddy covariance technique underestimates the total mean turbulent flux to some extent because of low pass filters (high frequency loss) and high pass filters (low frequency loss)[12,13]. Many cases could bring high frequency loss or low frequency loss. For example, spatial separation of sonic anemometers and IRGA instrumentation acts as a high frequency loss. Theoretical analytical and empirical approaches have been proposed to account for low and high frequency losses of turbulent fluxes. However, no standard method for estimating frequency response corrections is used, and the different correction methods do not always agree.

(5) The effect of advection. In eddy covariance system, it is assumed that advection of scalars (including CO_2), can be neglected[27]. Vertical advection is neglected by rotating the coordinate system so that the mean vertical velocity is always zero. However, non-zero values of mean vertical velocity and vertical advection are realistic. Two types of flows may make the assumption of negligible mean vertical advection problematic. First, horizontal heterogeneity in surface fluxes, can promote local circulations and vertical mo-

Table 4 Possible reasons for energy imbalance at ChinaFLUX sites[a)]

Cause of imbalance	Examples	$LE+H$	R_n-G-S	EBR	Affecting CO_2
Sampling	Different source areas				No
Instrument bias	Net radiometer biased				If SAT-3 or IRGA
Neglected energy sink	Storage above soil heat plates		+	–	No
High/low frequency loss	Sensor separation/large eddies	–		–	Yes
Advection	Regional circulation				Yes

a) Also shown is whether this effect is expected to underestimate (negative sign) or overestimate (positive sign) the turbulent fluxes ($LE+H$), available energy (R_n-G-S) and the energy balance closure ratio $(LE + H)/(R_n-G-S)$. The last column indicates whether this effect is relevant to interpretations of the CO_2 flux.

tions that seriously compromise the zero vertical velocity assumption. Similarly, even slight elevation gradients over a range of spatial scales can induce nocturnal drainage flows and advection near the surface during periods of strong static stability[15]. Previous researches suggested that terrain could affect the degree of energy balance closure. Stannard[14] suggested that there was a great lack of closure at sites across large range topographic variations. During nocturnal periods, especially when turbulence was weak (low friction velocity), the poor energy balance closure was consistent with the establishment of drainage flows that advect heat and water vapor to low terrain. To the point, the analyzed results of this study are accordant with previous researches[13,16,17,28].

Above-mentioned factors affecting energy balance closure are listed in table 4. This list is not totally comprehensive, but covers the primary reasons usually suspected for the energy imbalance. Table 4 also summarizes whether these sources of error may affect energy balance closure and CO_2 fluxes[18].

4 Conclusions

Using four different statistical methods, which were OLS, RMA, EBR and δ frequency distribution, this study evaluated energy balance closure and its spatio-temporal variation at ChinaFLUX sites.

(1) There was also a general lack of energy balance closure at ChinaFLUX sites. The degree of energy balance closure had a little difference among sites because of the properties variations of sites. The mean imbalance was in the order of 27%. On average, there were 80% observational data in the extent of double positive and negative standard deviation ($\pm 2\sigma$) of δ frequency distribution.

(2) Energy balance closure is typically poor during nocturnal periods, especially when the turbulent mixing is weak. The closure degree during nocturnal periods is lower than during daytime. According to diurnal variation of energy balance, during morning and evening transition periods, the change of EBR is drastic. Energy balance closure is better in the afternoon than in the morning.

(3) The degree of energy balance closure in winter was very low, and was higher in summer, in which a majority of EBR fluctuated near 1 value. Moreover, there was a phenomenon that turbulent energy fluxes were lower than available energy at forest sites but higher than available energy at grassland and cropland sites in winter.

(4) Energy balance closure improved with friction velocity intensifying. During daytime, there was a very weak trend for the OLS slope to increase with friction velocity. However, the OLS slope was smaller but more dependent on friction velocity during nocturnal periods. And when the mean friction velocity was below 0.5 ms^{-1}, the slope of the OLS regression during nocturnal periods increased rapidly with friction velocity.

Based on the analyzed results of this study, as concerning energy balance closure only, when estimating NEE and GPP of terrestrial ecosystems or doing other flux scientific research, we should select flux data during daytime in warm seasons (like growth seasons) and should filter the data by using the friction velocity (u*) of the empirical threshold, in order to reduce uncertainty in research. Using the flux data during nighttime and in winter, we should be careful and had better correct those data using chamber observational data.

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