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Two energy balance closure approaches: applications and comparisons over an oasis-desert ecotone

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Abstract: Studies of energy balance that rely on eddy covariance (EC) are always challenged by energy balance closure, which is mainly caused by the underestimations of latent heat flux (LE) and sensible heat flux (Hs). The Bowen ratio (BR) and energy balance residual (ER) approaches are two widely-used methods to correct the LE. A comprehensive comparison of those two approaches in different land-use types is essential to accurately correcting the LE and thus improving the EC experiments. In this study, two energy balance approaches (i.e., BR and ER) were compared to correct the LE measured at six EC sites (i.e., three vegetated, one mixed and two non-vegetated sites) in an oasis-desert ecotone of the Heihe River Basin, China. The influences of meteorological factors on those two approaches were also quantitatively assessed. Our results demonstrated that the average energy closure ratio ((LE+Hs)/(Rn–Gs); where Rn is the surface net radiation and Gs is the surface soil heat flux) was approximately close to 1.0 at wetland, maize and village sites, but far from 1.0 at orchard, Gobi and desert sites, indicating a significant energy imbalance at those three latter sites. After the corrections of BR and ER approaches that took into account of soil heat storage, the corrected LE was considerably larger than the EC-measured LE at five of six EC sites with an exception at Gobi site. The BR and ER approaches yielded approximately similar corrected LE at vegetated and mixed sites, but they generated dissimilar results at non-vegetated sites, especially at non-vegetated sites with low relative humidity, strong wind, and large surface-air temperature difference. Our findings provide insight into the applicability of BR and ER approaches to correcting EC-based LE measurements in different land-use types. We recommend that the BR-corrected and ER-corrected LE could be seriously reconsidered as validation references in dry and windy areas.

Keywords: energy balance closure; eddy covariance; Bowen ratio-energy balance approach; energy balance residual approach; Heihe River Basin

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1 Introduction

The energy exchanges within the land-atmosphere interface play a critical role in forming the Earth's climate systems (Stoy et al., 2013) and the role is explicitly expressed by energy balance. The balance includes three basic components: energy intake, energy expenditure and energy storage (Bray et al., 2003) and the three components are often tightly coupled through either positive or negative feedback mechanisms (Blundell et al., 2003). The energy balance exerts influence not only on the Earth's climate systems, but also on the hydrological cycles and the

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biogeochemical cycles (e.g., Meyers et al., 2004; Wild, 2008; Mercado et al., 2009; Moiwo and Tao, 2015).

The energy stored in the canopy layer is often negligible (Meyers and Hollinger, 2004; Haverd et al., 2007). If the influences of ice melt, biomass storage and advection on the energy balance are also negligible, the energy balance within the land-atmosphere interface (i.e., near the land surface) can be generally expressed as: Rn–Gs=LE+Hs (Meyers and Hollinger, 2004; Haverd et al., 2007). Where Rn is the surface net radiation and Gs the surface soil heat flux (Leuning et al., 2012); LE is the latent heat flux and Hs the sensible heat flux, both being measured using eddy covariance method (EC) (Twine et al., 2000; Baldocchi et al., 2001; Heusinkveld et al., 2004; Wang and Dickinson, 2012). Rn can be directly measured with satisfactory accuracy (Foken, 2008). Gs comprises the heat flux and the soil heat storage. It should be mentioned that neglecting the soil heat storage may result in inaccurate Gs estimations (Heusinkveld et al., 2004) and that the inaccuracy problem can be alleviated if the damping effects of soil temperature and moisture profiles are corrected (Yang and Wang, 2008; Leuning et al., 2012). It should be stressed that the heat fluxes (LE and Hs) measured using EC are usually underestimated (Wilson et al., 2002), and the sum of estimated latent and sensible heat fluxes (LE+Hs) is thus smaller than the available energy flux (Rn–Gs) (Wang et al., 2009; Franssen et al., 2010), resulting in energy balance closure (i.e., energy imbalance) (Kristensen et al., 1997; Mauder et al., 2006, 2007; Liu et al., 2009; Xu et al., 2013).

It should be reiterated that the energy balance closure (i.e., energy imbalance) is directly related to the EC-resulted underestimations of the latent and sensible heat fluxes (Aubinet et al., 1999; Wilson et al., 2002) and that it has been one of the major challenges in the studies of the energy exchange processes within the land-atmosphere interface (Oliphant et al., 2004; Oncley et al., 2007; Wang et al., 2009). The aforementioned energy balance closure problem has twofold implications: (1) how energy flux measurements should be interpreted, and (2) how these estimates should be corrected or calibrated with model simulations or/and field experiments (Twine et al., 2000). A number of methods have been proposed to correct the EC-measured energy fluxes (Castellví, 2008; Kidston et al., 2010; Liu et al., 2012), and the most frequently adopted methods are the Bowen ratio (BR) approach (Twine et al., 2000; Barr et al., 2012) and the energy balance residual (ER) approach (Schotanus et al., 1983; Amiro, 2009). The widely-used BR approach is quite simple: proportionally assigning the underestimated energy to LE and Hs (Twine et al., 2000; Wohlfahrt et al., 2009). The ER approach regards the LE as the energy balance residual (Rn–Gs–Hs) (Amiro, 2009) and this approach was mainly applied to vegetated regions. It should be particularly noted that the LE is highly dependent on the underlying surfaces and that it is thus essential to assessing the applicability of BR and ER approaches to different land-use types for advancing the EC-based studies of energy balance.

This study took advantage of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) project that established well-calibrated EC sites in an oasis-desert ecotone within the Heihe River Basin (Xu et al., 2013; Wang et al., 2015). Specifically, the EC-based LE values in different land-use types measured during the period from 25 June to 15 September (2012) were corrected using BR and ER approaches. The purpose was to assess the applicability of these two approaches to different land-use types for advancing the EC-based studies of energy balance. Again, neglecting the soil heat storage may result in inaccurate Gs estimations. In this study, the damping effects of soil temperature and moisture profiles were corrected to alleviate the inaccuracy problem. Furthermore, as the LE values, corrected either using BR approach or using ER approach, may be affected by meteorological factors, the influences of meteorological factors were also assessed.

2 Materials and methods

2.1 Study area

The study sites are situated in an oasis-desert ecotone of Zhangye City (38°51′N, 100°25′E; 1519 m a.s.l.) within the Heihe River Basin, Northwest China. The Heihe River Basin is the second largest inland river basin in China and covers an area of approximately 130×10^3 km^2. The study area, an oasis-desert ecotone of Zhangye City, is characterized by a continental climate with a long dry season (from October to May of next year) and a short rainy season (from June to September). The minimum, maximum and annual mean temperatures are –31.0°C, 39.1°C and 7.4°C, respectively. Average annual precipitation is 115.6 mm and average annual evaporation is as high as 2107.1 mm.

2.2 Experiment design and data collection

The data used in this study were collected from six EC sites of the HiWATER project (Fig. 1) (Li et al., 2013). And, all those data from the measuring period of 25 June to 15 September (2012) were downloaded from the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn) (Liu et al., 2011; Xu et al., 2013). It should be stressed that the downloaded LE and Hs data were converted from the *in situ* observed data. The conversion involved the following data and steps: spike detection, H_2O lag relative to the vertical wind component, sonic virtual temperature (Schotanus et al., 1983), coordinating rotation (Wilczak et al., 2001), density fluctuation (Webb et al., 1980), and frequency response (Lee et al., 2004; Liu et al., 2012). The six EC sites were classified into three land-use categories: vegetated sites (maize land, orchard land and wetland), mixed site (village), and non-vegetated sites (desert and Gobi). The vegetated and mixed sites represent the oasis area, whereas the non-vegetated sites represent the desert area. The descriptive information of each site is listed in Table 1.

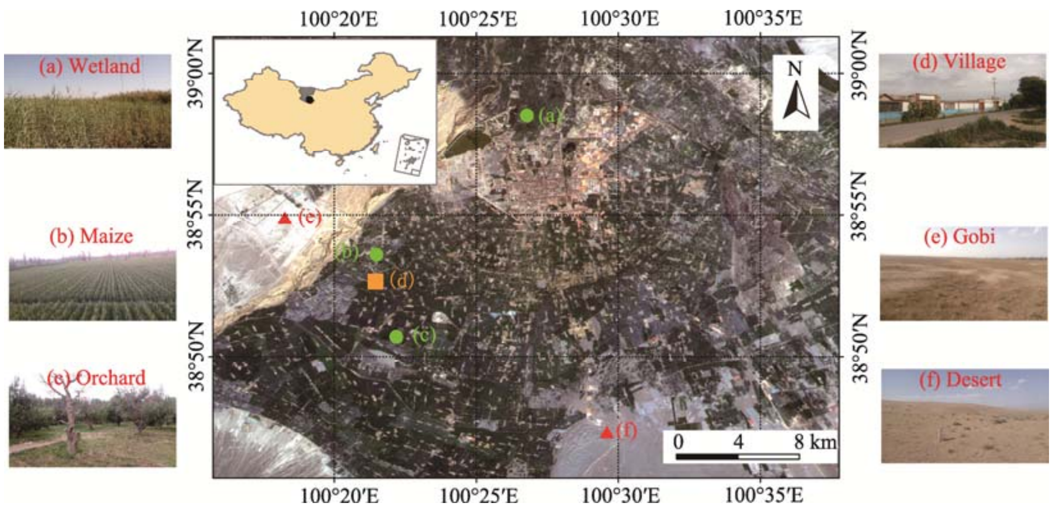

Fig. 1 Locations of EC (eddy covariance) sites and land-use types of the EC sites

Table 1 Descriptive information of EC (eddy covariance) sites

Site		Longitude	Latitude	Altitude (m)	EC height (m)
Vegetated	Wetland	100°26′45″E	38°58′30″N	1460	5.2
	Maize	100°22′19″E	38°51′21″N	1556	34.0
	Orchard	100°22′12″E	38°50′41″N	1559	7.0
Mixed	Village	100°21′28″E	38°52′40″N	1561	4.2
Non-vegetated	Gobi	100°18′14″E	38°54′54″N	1562	4.6
	Desert	100°29′34″E	38°47′20″N	1594	4.6

The LE data and the Hs data measured using EC (hereinafter called LE and Hs, respectively) at an interval of 30 min were used in this study. It deserves mentioning that the following two relevant researches provided quite useful references to this study: (1) the EC metrics were inter-compared and validated over the Gobi for the period of 14–24 May (2012) by Xu et al. (2013) and (2) data consistency was insured by the instrument inter-calibration processes (including uniform data processing steps and standards) (Wang et al., 2015). To avoid the underestimations of LE and Hs (Liu et al., 2012), we only selected daytime (08:00–17:30, local solar time) data and corrected the original LE data using both the BR and ER approaches.

In the field, the Rn and Gs were measured by pyranometers/pyrgeometers and heat flux plates, respectively. In this study, the Rn and Gs data were collected at an interval of 10 min and then averaged into 30-min data to match the 30-min LE and Hs data. The auxiliary data were also field collected and they include soil data (i.e., moisture and temperature) measured by soil moisture and temperature probes and air data (i.e., relative humidity, wind speed and air temperature) measured by automatic meteorological stations. In addition, the upward long-wave radiation was also measured.

2.3 Methods

2.3.1 Soil heat storage correction for Gs

Gs comprises the heat flux at certain soil depths (at 6 cm in HiWATER) and the soil heat storage above certain soil depths (i.e., above 6 m). Again, it should be stressed that neglecting the soil heat storage may result in inaccurate Gs estimations (Heusinkveld et al., 2004) and that the damping effects of soil temperature and moisture profiles can be corrected to alleviate the inaccuracy problem (Yang and Wang, 2008; Leuning et al., 2012). In this study, the accuracy of Gs estimations was improved by correcting the damping effects of soil temperature and moisture profiles (Yang and Wang, 2008):

$$Gs = G\left(z_{ref}\right) + \frac{1}{\Delta t}\sum_{z_{ref}}^{z}\left[\rho_s c_s\left(z_i, t+\Delta t\right)T\left(z_i, t+\Delta t\right) - \rho_s c_s\left(z_i, t\right)T\left(z_i, t\right)\right]\Delta z. \quad (1)$$

Where, z (m) is the soil depth, Δz (m) the measuring interval of soil profiles, z_{ref} (m) the depth of soil heat plate; $G(z_{ref})$ (W/m^2) is the heat flux measured by soil heat flux plate, T (K) the soil temperature, t (s) the sampling time, Δt (s) the sampling interval; and $\rho_s c_s$ (J/(kg•K)) is the soil heat capacity, which can be calculated based on soil water content (θ) and soil porosity (θ_{sat}) (i.e., $\rho_s c_s \approx 2.1\times10^6\times(1-\theta_{sat})+4.2\times10^6\times\theta$).

2.3.2 Bowen ratio (BR) correction approach

The BR approach uses the independent Rn and Gs measurements to correct the EC-based LE measurements (Twine et al., 2000). The Bowen ratio (β) is expressed as: $\beta=Hs/LE$ (Bowen, 1926). Ideally, the available energy flux (Rn–Gs) is equal to the sum of measured latent and sensible heat fluxes (LE+Hs). Thus, if the available energy flux is known, then the LE can be expressed by the available energy flux and Bowen ratio (β) as follows:

$$BRLE = \frac{1}{1+\beta}\left(Rn - Gs\right). \quad (2)$$

Where, $BRLE$ (W/m^2) is the Bowen ratio-corrected LE with soil heat storage correction; Rn (W/m^2) is the net radiation; and Gs (W/m^2) is the corrected soil heat flux with soil heat storage correction. In practice, weights are assigned to LE and Hs according to the Bowen ratios (Wilson et al., 2002).

2.3.3 Energy balance residual (ER) correction approach

Assuming that Rn, Gs and Hs can be accurately measured, then the relatively accurate LE can be derived from the energy balance expression Rn–Gs=LE+Hs (Schotanus et al., 1983; Amiro, 2009). Accordingly, the corrected LE is as follows:

$$ERLE = Rn - Gs - Hs. \quad (3)$$

Where, $ERLE$ (W/m^2) is the energy balance-corrected LE with soil heat storage correction, whereas Hs (W/m^2) is the sensible heat flux directly measured by EC and is often underestimated because of the shortcomings of the triaxial sonic anemometer (Kristensen et al., 1997; Lee et al., 2004).

2.3.4 Influences of advection on energy balance closure

The magnitude of energy balance closure is related to the advection to some degree (Foken, 2008). The advection (X; W/m^2) is defined as follows: $X=\Delta/(\Delta+\gamma)\times(Rn-Gs)-LE$ (McNaughton, 1983).

Where, Δ is the slope of the saturated vapor pressure at certain air temperatures and *γ* the psychometric constant. *X* is negative for advective enhancement and positive for advective depression. Moreover, the percentage contribution (R_{ad}) of advection (*X*) to LE is defined as follows: $R_{ad}= -X/LE$ (Smith et al., 1997). Based on *X* and R_{ad}, the influences of advection on energy balance closure at all EC sites can be evaluated.

2.3.5 Indices for accuracy assessment

Bias, standard deviation (SD) and root mean square error (RMSE) expressed in Equations 4–6 (Nagol et al., 2009) were used to evaluate the acceptancy of the two correction approaches:

$$Bias = \frac{\sum_{i=1}^{n} data_i - ref_i}{n}. \tag{4}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}\left(Bias_i - \overline{Bias_i}\right)^2}{n}}. \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Bias_i - \overline{Bias_i})^2}{n}}. \tag{6}$$

Where, $data_i$ is the data to be evaluated, ref_i the reference of evaluation; $\overline{Bias_i}$ is the average value of *Bias* and *n* is the number of data pairs used in the comparisons.

In addition, the linear regression was used to analyze the agreements or discrepancies among the LE data sets. The correlation coefficient (R^2), Slope and Intercept of the linear fit were subsequently obtained (Squires, 2001):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(data_i - ref_i\right)^2}{\sum_{i=1}^{n}\left(data_i - \overline{ref}\right)^2}. \tag{7}$$

$$Slope = \frac{\sum_{i=1}^{n} data_i\left(ref_i - \overline{ref}\right)^2}{\sum_{i=1}^{n}\left(ref_i - \overline{ref}\right)^2}. \tag{8}$$

$$Intercept = \frac{\sum_{i=1}^{n}\left(data_i - Slope \times ref_i\right)}{n}. \tag{9}$$

Where, $\overline{ref}$ is the average of the references. The agreement is better when the regression line is closer to the 1:1 line.

3 Results

3.1 Environmental variables and energy fluxes

Table 2 shows the environmental variables and the measured energy fluxes at six EC sites. It should be noted that the soil moisture in the wetland was set as 50.00%. The topsoil moisture (at 2 cm depth) at six EC sites generally increased with increasing vegetation coverage. On the contrary, the surface temperature generally decreased with increasing vegetation coverage with the air temperature being almost similar at all six sites. In general, the relative humidity was higher at vegetated sites (e.g., 45.37% at wetland site) than at non-vegetated sites (e.g., 39.60% at desert site). However, the opposite was true for wind speed (e.g., 1.63 m/s at orchard site; 3.62 m/s at Gobi site).

With respect to the energy fluxes, Rn and LE were higher at vegetated sites than at non-vegetated sites. In contrast, Hs was considerably lower at vegetated sites (20–60 W/m^2) than at non-vegetated sites (approximately 120 W/m^2). Moreover, the energy fluxes at mixed site (village) fell in the range between those at vegetated sites and those at non-vegetated sites. As shown in Table 2, the energy closure residual (i.e., the difference between Rn–Gs and Hs+LE) was higher at orchard and desert sites (70–110 W/m^2) than at other sites (<20 W/m^2). The energy closure ratio (i.e., (Hs+LE)/(Rn–Gs)) (i.e., another expression of energy imbalance) was close to 1.0 at wetland, maize and village sites. The ratio was however far from 1.0 at orchard, Gobi and desert sites, indicating a significant energy imbalance at those three sites.

Table 2 Statistics of environmental variables and energy fluxes at six EC sites

Parameter	Statistic variable	Site					
		Wetland	Maize	Orchard	Village	Gobi	Desert
SM (%)	Mean	50.00	21.40	26.80	14.63	13.89	6.40
	SD	0.00	6.64	5.97	4.22	3.96	1.80
	Max	50.00	52.40	45.87	24.31	23.84	10.21
	Min	50.00	10.34	17.67	4.16	6.63	3.02
Ts (K)	Mean	297.38	299.93	295.54	308.65	305.59	310.55
	SD	4.60	4.99	3.74	9.51	8.59	9.63
	Max	306.46	314.35	304.87	328.27	325.51	328.60
	Min	277.63	280.93	279.74	282.38	286.76	286.78
RH (%)	Mean	45.37	48.24	45.24	43.96	42.13	39.60
	SD	16.72	15.82	16.69	17.74	18.50	17.46
	Max	91.97	100.00	96.10	93.07	89.47	85.77
	Min	11.91	13.72	11.87	9.10	8.34	11.22
WS (m/s)	Mean	2.57	2.27	1.63	2.08	3.62	3.13
	SD	1.57	1.16	0.75	0.93	2.04	1.41
	Max	9.35	8.49	5.71	7.50	14.27	8.76
	Min	0.14	0.41	0.00	0.62	0.00	0.30
Ta (K)	Mean	296.56	296.13	296.86	296.96	295.88	296.65
	SD	4.59	4.42	4.40	4.50	4.44	4.61
	Max	307.84	306.26	307.47	307.54	304.97	309.10
	Min	279.00	278.51	281.36	282.93	282.82	280.84
LE (W/m^2)	Mean	277.89	356.28	281.27	132.52	77.27	73.40
	SD	131.14	173.10	134.67	63.18	77.76	57.30
	Max	658.43	1104.60	693.11	387.07	575.51	366.71
	Min	7.48	4.43	18.09	9.11	–45.28	0.07
Hs (W/m^2)	Mean	25.44	38.21	57.08	94.04	119.80	117.96
	SD	48.46	59.78	59.14	57.42	81.97	74.50
	Max	239.25	314.88	280.44	368.33	401.40	351.49
	Min	–128.70	–71.81	–104.69	–35.47	–14.47	–6.12
Rn (W/m^2)	Mean	403.29	439.23	496.13	356.42	308.78	336.80
	SD	195.99	189.37	213.31	162.62	159.88	164.88
	Max	795.13	747.90	899.00	768.13	693.07	806.43
	Min	–14.58	–3.94	–6.89	–7.90	–50.33	–33.12
Gs (W/m^2)	Mean	93.00	33.77	57.42	120.61	131.30	73.98
	SD	75.98	57.50	94.87	111.51	112.92	56.28
	Max	270.19	266.71	614.40	386.50	461.02	211.38
	Min	–72.19	–260.68	–191.19	–313.74	–216.65	–57.68
Rn–Gs–LE–Hs (W/m^2)	Mean	6.96	10.98	100.36	9.26	–19.60	71.46
	SD	65.77	115.60	115.99	84.20	70.74	70.79
	Max	188.25	353.47	692.35	344.64	253.57	386.18
	Min	–258.02	–494.83	–527.57	–224.85	–309.42	–152.95
(LE+Hs)/(Rn–Gs)	Mean	1.00	0.99	0.80	1.02	1.16	0.76
	SD	0.33	0.36	0.57	0.56	3.45	1.08
	Max	6.80	3.36	12.43	8.74	67.48	7.65
	Min	0.26	–0.07	–2.49	–5.10	–40.24	–24.72

Note: SM, soil moisture; Ts, surface temperature; RH, relative humidity; WS, wind speed; Ta, air temperature; Rn, surface net radiation; Gs, surface soil heat flux; LE, latent heat flux measured by EC; Hs, sensible heat flux; Rn–Gs–LE–Hs, energy closure residual; (LE+Hs)/(Rn–Gs), energy closure ratio; SD, stand deviation; Max, maximum; Min, minimum.

As shown in Figure 2a, advective enhancement was indicated by negative advections ranging from –50 to –45 W/m^2 at wetland and maize sites and advective depression was suggested by positive advections ranging from 50 to 126 W/m^2 at other sites. The percentage contributions of advection to LE (Fig. 2b) indicated that the advection significantly affects the LE at non-vegetated sites (Gobi and desert).

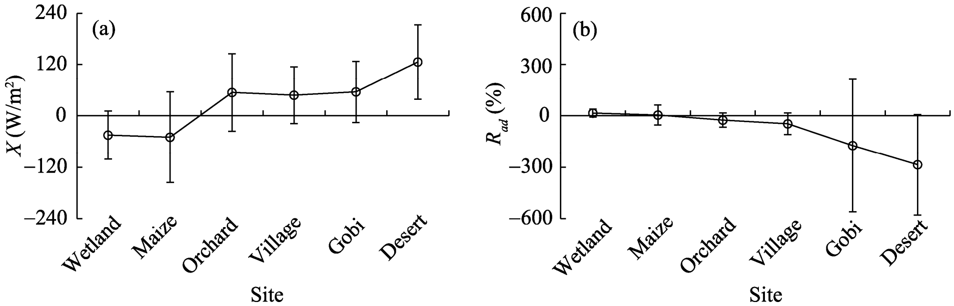

Fig. 2 (a) Mean (marked by cycles) and standard deviation (marked by bars) of the advection (X) and (b) percentage contributions of advection to LE (R_{ad}) at six EC sites

3.2 Comparison of BR and ER approaches

Figure 3 shows the comparisons between LE (i.e., latent heat flux) and BRLE (i.e., Bowen ratio-corrected LE with soil heat storage correction) and between LE and ERLE (i.e., energy balance-corrected LE with soil heat storage correction) at six EC sites. Our comparisons demonstrated that both the BR and ER approaches were able to correct the negative biases in LE measurements. The site-to-site comparison revealed that except at village site (see Fig. 3-a4), BRLE were well comparable to LE at all of other five sites (especially at wetland, maize and orchard sites) and the good comparability was expressed by higher R^2 values and lower Slope values. It should be pointed out that the corrected LE values were significantly higher than the EC-measured LE values, further confirming the underestimation problems of EC-based LE measurements. For example, the BR-corrected LE was about 10 W/m^2 higher than the EC-measured LE at wetland, maize and village sites and was up 85 W/m^2 higher at orchard site (see Fig. 3-a1–a4). The ER-corrected LE was also about 10 W/m^2 at wetland, maize and village sites and was up to 100 W/m^2 at orchard site (see Fig. 3-b1–b4). The exception occurred at Gobi site where BR-corrected LE was about 4 W/m^2 lower than the EC-measured LE (see Fig. 3-a5) and where ER-corrected LE was about 20 W/m^2 lower than the EC-measured LE (see Fig. 3-b5).

The bottom two panels of Figure 3 (i.e., c1–c6) show the comparisons between BRLE and ERLE at all six EC sites. BRLE was in good agreement with ERLE at vegetated and mixed sites (R^2>0.90). In contrast, relatively large discrepancies existed between ERLE and BRLE at two non-vegetated sites (R^2<0.90). As shown in Table 3, the difference was smallest at wetland site (Bias=1.73 W/m^2; RMSE=12.06 W/m^2) and largest at desert site (Bias= –44.41 W/m^2; RMSE=66.90 W/m^2). Overall, the BR and ER approaches yielded similar results at vegetated and mixed sites, and larger discrepancies occurred at non-vegetated sites.

3.3 Influences of meteorological factors on BR and ER approaches

In this study, wind speed, relative humidity, and temperature difference between land surface and air were chosen to analyze the influences of meteorological factors on BR and ER approaches. The reasons are as follows: (1) they are the most important meteorological factors; (2) the wind speed may affect the advection flux; (3) the humidity may affect the signal frequency for gas analyzer; and (4) the temperature difference between land surface and air may affect the air dynamics below the measurement height. As shown in Figure 2b, the percentage contributions of advection to LE indicated that the advection significantly affects the LE at non-vegetated sites (Gobi and desert), we thus compared BRLE and ERLE at different levels of wind speed, air humidity and surface-air temperature difference at non-vegetated sites (Table 4; Fig. 4).

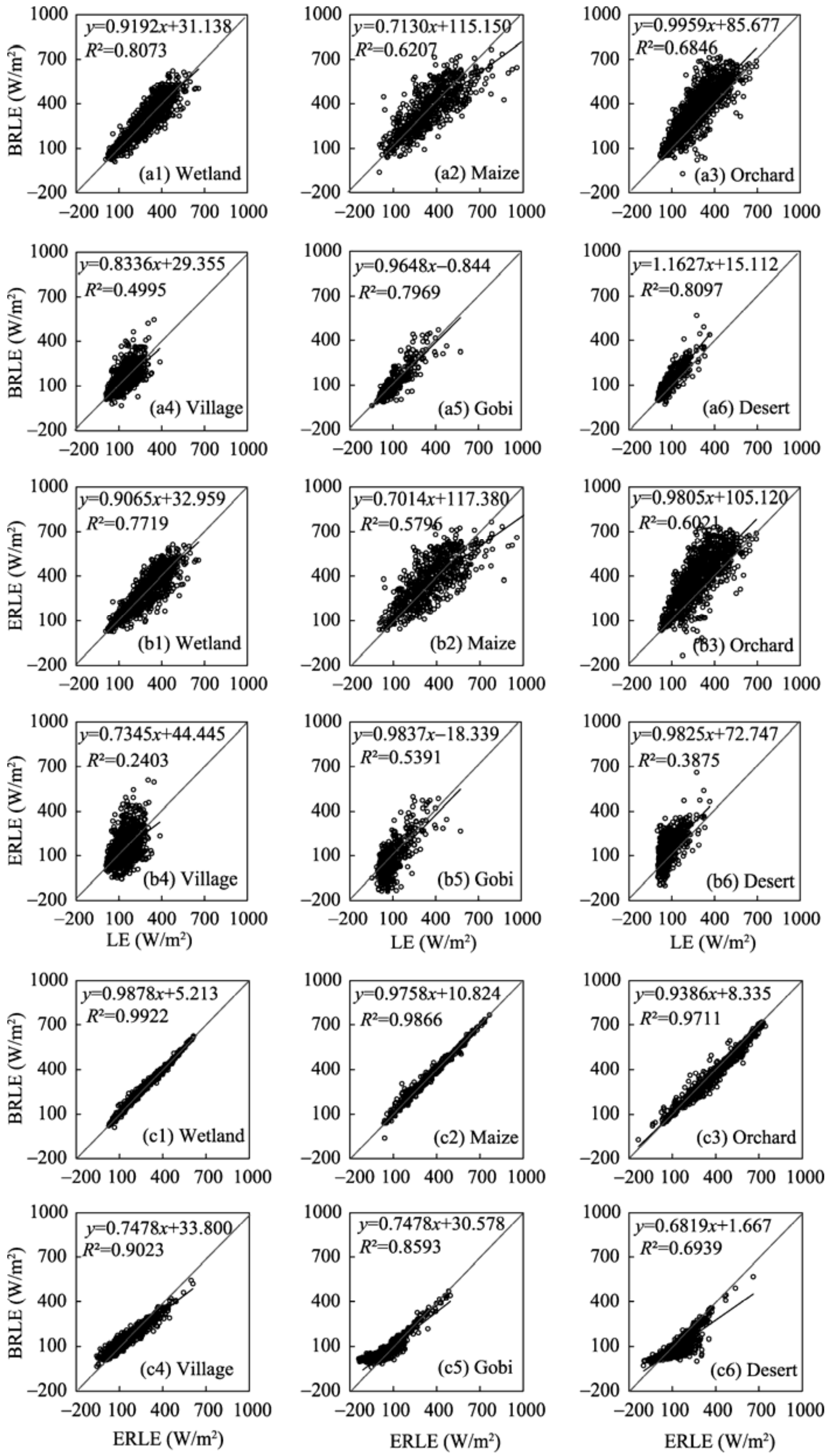

Fig. 3 Comparisons between LE and BRLE (a1–a6), LE and ERLE (b1–b6), and ERLE and BRLE (c1–c6) at six EC sites. LE, latent heat flux measured by EC; BRLE, Bowen ratio-corrected LE with soil heat storage correction; ERLE, energy balance residual-corrected LE with soil heat storage correction.

Table 3 Statistics of comparisons between LE and BRLE, LE and ERLE, and BRLE and ERLE at six EC sites

Item	Statistic variable (W/m^2)	Site					
		Wetland	Maize	Orchard	Village	Gobi	Desert
LE vs BRLE	Bias	8.70	12.92	84.51	7.31	–3.57	27.05
	SD	59.84	108.52	90.83	53.76	37.97	33.62
	RMSE	60.44	109.20	124.03	54.24	38.11	43.14
LE vs ERLE	Bias	6.96	10.98	99.63	9.26	–19.60	71.46
	SD	65.77	115.60	107.13	84.20	70.74	70.79
	RMSE	66.10	116.03	146.26	84.67	73.36	100.56
BRLE vs ERLE	Bias	1.73	1.94	–15.11	–1.95	16.03	–44.41
	SD	11.94	18.53	29.42	33.35	41.03	50.06
	RMSE	12.06	18.62	33.06	33.40	44.03	66.90

Note: BRLE, Bowen ratio-corrected LE with soil heat storage correction; ERLE, energy balance residual-corrected LE with soil heat storage correction; SD, stand deviation; RMSE, root mean square error.

Table 4 Statistics of comparisons between BRLE and ERLE at non-vegetated sites at different levels of relative humidity (RH), wind speed (WS) and surface-air temperature difference (Ts–Ta)

Parameter	Classification	Gobi site			Desert site		
		Bias	SD	RMSE	Bias	SD	RMSE
		(W/m^2)			(W/m^2)		
WS (m/s)	<2	10.90	32.40	34.06	–44.31	38.23	58.46
	2–4	21.59	41.67	46.87	–41.36	44.96	61.06
	>4	10.38	43.06	44.21	–50.80	66.12	83.26
RH (%)	<30	25.57	46.34	52.83	–46.74	55.30	72.34
	30–60	17.52	41.01	44.54	–48.65	50.54	70.11
	>60	–2.36	22.46	22.51	–24.55	23.33	33.80
Ts–Ta (K)	–5–5	1.02	38.60	38.53	–9.14	17.88	20.00
	5–15	18.06	38.08	42.08	–30.48	43.21	52.83
	15–25	31.66	41.40	52.04	–65.77	51.88	83.73

Wind speed was divided into <2, 2–4 and >4 m/s, representing gentle, moderate and strong winds, respectively. Generally speaking, the discrepancy between BRLE and ERLE increased with increasing wind speeds. That is, both the R^2 values and the Slope values were lower at high wind speed (>4 m/s) than those at low wind speed (<2 m/s). The Bias, SD and RMSE, however, refused to show any patterns (see Fig. 4-a1–a6).

Relative humidity was divided into <30%, 30%–60% and >60%, corresponding to dry, moderate and moist air conditions, respectively. As demonstrated by both the R^2 values and the Slope values, the higher the air moisture, the better the agreement between BRLE and ERLE was (see Fig. 4-b1–b6). The lowest Bias, SD and RMSE values at highest level of air humidity also suggested that the difference between BRLE and ERLE was smallest under the highest moisture condition (Table 4).

The surface-air temperature difference was divided into –5–5, 5–15 and 15–25 K, corresponding to slight, moderate and large temperature differences, respectively. In general, the discrepancy between BRLE and ERLE was larger at larger surface-air temperature difference (Fig. 4-c1–c6). That is, both the R^2 values and the Slope values were higher at lower surface-air temperature difference (–5–5 K) than those at larger surface-air temperature difference (15–25 K). The highest Bias, SD and RMSE values also indicated that the agreement between BRLE and ERLE was poorest at the largest surface-air temperature difference (Table 4).

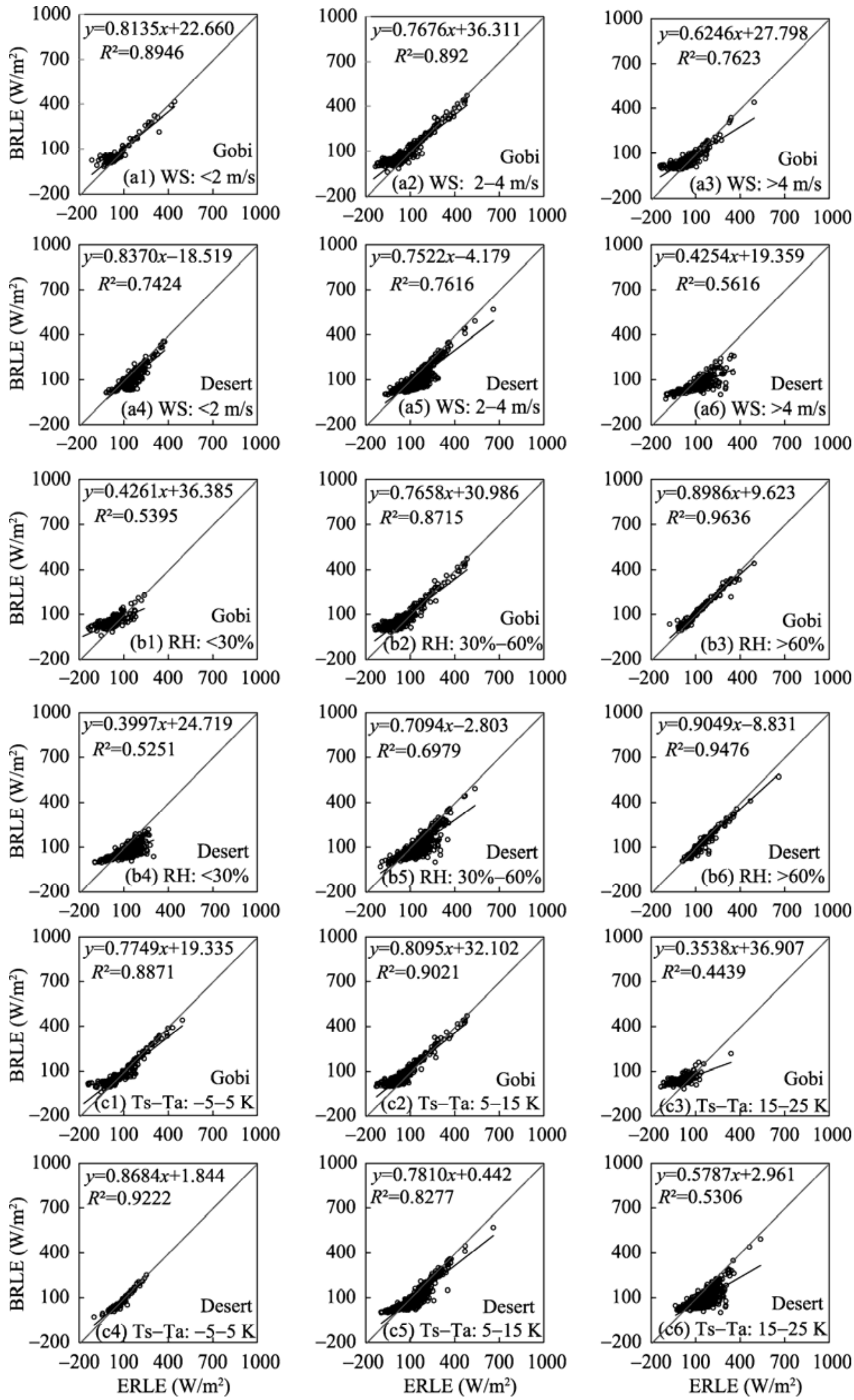

Fig. 4 Comparisons between BRLE and ERLE at different levels of WS (a1–a6), RH (b1–b6) and Ts–Ta (c1–c6) at non-vegetated sites (Gobi and desert sites). WS, wind speed; RH, relative humidity; Ts–Ta, surface-air temperature difference.

4 Discussion

As mentioned before, the energy balance closure (i.e., energy imbalance) has been one of the major challenges in the studies of energy exchange processes within the land-atmosphere interface. There are many possible causes for energy balance closure and these causes are directly or indirectly related to following factors: canopy layer, spatial scale, soil heat storage, horizontal advection, heat storage in the developing boundary layer below the measurement height, frequency response of the sensors, measuring errors of turbulent fluxes, etc. (Foken, 2008). However, only a small number of these factors dictate the energy balance closure in a specific region. For example, the energy stored in the canopy layer has a non-negligible influence on energy balance in a forested region (Lindroth et al., 2010). Another example is the spatial scale problem (discrepancies of footprint among instruments) that may exert a significant influence on energy balance in a region with inhomogeneous land surfaces. In a region with poor vegetation and high wind speed, the horizontal advection may affect the energy balance (Foken, 2008). In our study, the percentage contributions of advection to LE were rather high (ranging from –286% to –176%) at non-vegetated sites (Gobi and desert) with high wind speed (>4 m/s).

Many approaches were proposed to correct the energy balance closure and BR and ER approaches were most frequently adopted (Twine et al., 2000; Amiro, 2009; Allen et al., 2011). In terms of the physics underlying the BR approach, EC-based measurements underestimate turbulent fluxes and the underestimations of LE and Hs are in accordance with the Bowen ratios. Therefore, this approach actually corrects the energy imbalance by distributing the residual energy according to the Bowen ratios. Mathematically speaking, the BR approach assumes that LE and Hs have similar levels of accuracies (Twine et al., 2000). However, based on *in situ* observations, EC is more accurate for estimating Hs than for estimating LE (Kristensen et al., 1997; Mauder et al., 2006, 2007; Xu et al., 2013). Furthermore, small seasonal differences in the random error of Hs and large seasonal differences in the random error of LE were documented (Richardson et al., 2006). Thus, cautions should be exercised when applying the BR approach to the circumstances where the accuracy levels of Hs and LE measurements differ significantly (Kidston et al., 2010). ER approach is based on energy balance principle (Rn–Gs=LE+Hs), assuming that the available energy flux (Rn–Gs) is equal to the sum of measured latent and sensible heat fluxes (LE+Hs). Obviously, this approach relies only on the measurements of Rn, Gs and Hs (Allen et al., 2011). Therefore, the ER approach may provide more accurate LE data compared to the BR approach if the accuracies of Rn, Gs and Hs measurements can be insured (Burba and Anderson, 2010; Allen et al., 2011; Liu et al., 2012; Hu et al., 2015). However, ER approach may not work well when energy storage value is larger than other flux values (Meyers and Hollinger, 2004; Amiro, 2009).

In this study, BRLE was in good agreement with ERLE at vegetated and mixed sites. But, a relatively large discrepancy existed between ERLE and BRLE at two non-vegetated sites and the discrepancy was even larger under strong winds at desert area. This is likely due to the advective flux divergence (Foken, 2008). Therefore, the acceptancy of BR approach is different from that of ER approach at desert area, especially under strong winds. The difference between BRLE and ERLE was smallest under moist air conditions likely due to more accurate LE values under high air humidity conditions (Moncrieff et al., 1997). The agreement between BRLE and ERLE was poorer at larger land-air temperature differences and this may be attributable to the unknown air dynamics below the measurement height (Leuning et al., 2012). The difference between BRLE and ERLE is likely related to the degree of energy balance closure. The energy closure ratio was approximately close to 1.0 at wetland, maize and village sites but was far from 1.0 at orchard, Gobi and desert sites, indicating a significant energy imbalance at those three latter sites. Generally, ER approach and BR approach yielded similar results over the oasis area but generated dissimilar results over the desert area. According to our study, ER approach seems to be more reasonable for LE correction in desert area compared to BR approach. In addition, the ER approach seems to be a better alternative than the BR approach if EC-based LE measurements are severely underestimated. All in all, selection of approaches is actually dependent on the circumstances (Verstraeten et al., 2008; Li et al., 2009).

5 Conclusions

EC system has become a primary method for measuring LE, but it usually underestimates the LE, resulting in energy balance closure. To obtain more accurate LE in the studies of energy balance, we applied BR and ER approaches to correct the original EC-based LE measurements at six EC sites of the HiWATER. Our study showed that the mean energy closure ratio was close to 1.0 at wetland, maize and village sites but far from 1.0 at orchard, Gobi and desert sites, indicating a significant energy imbalance at those three latter sites. ER approach and BR approach yielded similar results over the oasis area but generated dissimilar results over the desert area. And, the difference was especially large over desert area when air humidity was low, wind was strong, and surface-air temperature difference was large. ER approach may be more reliable than BR approach for LE correction in desert region. To sum up, cautions should be exercised when selecting LE-correcting approaches.

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