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On the factors influencing surface-layer energy balance closure and their seasonal variability over semi-arid loess plateau of Northwest China

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Abstract

In the context of September 2006–August 2010 eddy covariance data of the Semi-Arid Climate Change and Environment Observatory, Lanzhou University (SACOL) as a platform of the Key Laboratory of Semi-Arid Climate Change, Ministry of Education, an intensive study is performed of the SACOL data quality and energy balance closure (EBC) characteristics on a seasonal basis, the EBC impacts of the flux contribution from the target source zone, the low-frequency part of the turbulence spectra, turbulent mixing intensity and diverse schemes for surface soil heat fluxes. Evidence suggests that (1) through the steady state test (SST) and integral turbulence characteristics (ITC) tests as well as analysis of flux contribution from target area to the EBC, it is found that most of the eddy covariance data are within a domain of effective quality. The valid data account for 77.5, 75.4, 68.3 and 61.6% of seasonal total for spring, summer, autumn and winter, respectively; (2) the EBC shows its appreciable seasonal variability, with the energy residual making up 19.0, 14.8, 11.6 and 7.7% of net radiation in winter, summer, autumn and spring, respectively; (3) (i) Flux contribution from the target zone has greater EBC impact and as the flux contribution in percentage increases, EBC is correspondingly improved. Even the percentage reaches 100%, the energy balance fails to be closed entirely. (ii) The Ogive function analysis shows that the EBC suffers the effect of relatively small (maximum) low-frequency turbulent flux in spring and summer (winter). (iii) Turbulence intensity exerts noticeable impact on the EBC; when turbulent mixing arrives at certain intensity, the EBC is in an optimal state and stabilized. (iv) Different schemes of surface soil thermal flux have significant effect on the EBC.

1 Introduction

The source/sink of matter and energy for atmospheric environment are in the planetary boundary layer. The surface layer serves as a major region of the exchange of turbulent

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energy, vapor and CO₂ between air and land. Their exchange properties exert innegligible impact on atmospheric motion and surface environmental condition, and thus, the study of these issues serves as the dominant aspects of land–surface processes.

The law of energy conservation is the first thermodynamic law and a universal law, too. Thus, the exchanges of energy and matter in air-land interaction must follow the conservation law without exception. However, not until the late 1980s did many experiments show the energy balance to be unclosed, with the EBC accounting for about 70~80% (Tsvang et al., 1991; Wilson et al., 2002; Li et al., 2005). Therefore, to search for causes of energy balance unclosure (EBU) of observed energy is one of the important issues of exploring energy balance. In their Energy Balance Experiment (EBEX), Oncley et al. (2007) made detailed study of the EBC effect of the principal components of surface energy equilibrium, arriving at the conclusion that the advection between canopy top and flux measuring height is likely to have impact upon EBU. Panin (1998) indicated that the EBU bears a relation to a complicated underlying surface, because a heterogeneous surface would generate even larger-time-scale eddy than those measured by the eddy covariance method, implying that the low-frequency component of the turbulence spectra would affect the production of different-degree EBC (Foken et al., 2006). Wilson et al. (2002) noted that the heat storage term is underestimated greatly for morning EBC based on data over a range of FLUXNET points. Besides, the related causes are addressed in different aspects by Foken (2006) and Cava (2008) among others. And now, the energy balance closure (EBC) is an exceedingly prominent problem of the air-earth interaction study. Causes of the EBU are not entirely understood, and so far the explanations are imperfect. Here we study the problem using long term data in semi-arid area of the loess plateau.

As a region of unique landform and climate and thus a special zone of arid and semi-arid climate (such regions constituting about 30% of the global land), the northwestern loess plateau of China acts as an innegligible portion of air-earth interactions for study. The SACOL is situated in such a landform, working for nearly 5 years. This present study gives sufficient examination of long-term EBC features using the SACOL eddy

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covariance (EC) dataset obtained in September 2006–August 2010. The intensive research focuses on the factors responsible for seasonal EBU, aiming at examining the EBC effect of the factors consisting of (1) the flux contribution from the target source zone, (2) contribution of the low-frequency part of the turbulence spectra, (3) turbulent mixing and (4) different schemes of surface soil heat flux in order to explore the impact upon EBC and thus the causes of EBU in the study region. This is of much significance to improving land surface process parameterization schemes and models.

2 Observation site, data quality control and calculating methods

2.1 Observation site

The SACOL was situated at Mt. Tsui Ying at the elevation of 1965.8 m in 35°57'46'' N, 104°8'13'' E, covering 120 Chinese Mu, 48 km away from the center of Lanzhou City and also located in a typical loess-plateau landform with the summit in a primarily natural condition covered with protophyta. The site with its surroundings suffered little or no human effect so that it represented a primary regime of landform and vegetation in an arid and semi-arid climate of the loess plateau (Huang et al., 2008). The present study is conducted by means of 2006–2010 eddy covariance (EC) from the SACOL eddy covariance observing system, which was a three-axis Sonic Anemometer (CSAT3), and an opened path infrared CO₂/H₂O analyzer (LI-7500, LI-COR) (working at 3.0 m above ground; output data are 10 Hz) on a seasonal scale, the year being divided into spring (March–May), summer (June–August), autumn (September–November) and winter (December–February).

2.2 Data quality assessment and control

Due to blackout and instrumental breakdown there were observation missing data making up roughly 4.25% of the total during the observational period, with the corresponding figures of 3.47% and 0.77% of the total for spring and summer, respectively, and

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data were continuous in the main for the other seasons, whose missed data made up approximately 0.01% of total altogether. The eddy covariance (EC) had to be pre-processed before use as well as post-treatments for the purpose of quality analysis and control. And the related processing was conducted of SACOL turbulent pulse data given by the eddy covariance meter by means of the software downloaded from the website <http://www.geos.ed.ac.uk/abs/research/micromet/Edire/>. This software EdiRE dealt with pre-processing of high-frequency turbulence data, parameter-correlation correction and data quality control (Mauder et al., 2007) in order to obtain the average period (usually 30 min) mean wind, pressure, temperature, sensible/latent heat flux, CO₂ flux and other environmental variables, together with the multi-file treatment done at the same time.

Quality control of data serves as an indispensable link of the study of turbulence, illustrated below.

(1) Because of diverse causes, the dataset had invalid measurements due to their non-steady state and deviation from turbulence features, and these data had to be eliminated before the analysis of flux characteristics. A final quality was obtained on the basis of the steady-state test (SST) and integral turbulence characteristics (ITC) test (Foken et al., 1996). And the SST and ITC results in combination with quality control standards (Foken et al., 2004) were used to process the 2006–2010 SACOL data for their quality assessment and control. These tests were made to analyze primitive high-frequency measurements, including horizontal/vertical wind, temperature, vapor and CO₂ concentration. The ITC tested model result used in this work was the parameterization finding of Merry and Panofsky (1976) and, to remove effect due to uncertainties of u and T_s , the ITC test was done just of the vertical wind component w (Zuo et al., 2009).

(2) In view of the fact that surface properties had impact on observed fluxes, analysis of percentage flux contribution from the target zone allowed us to correctly assess the impact on fluxes of these surface characteristics (Rebmann et al., 2005; Gockede et al., 2008). The flux contributions in percentage (fp) from the target zone were computed

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and classified into 7 levels, i.e., fp class 1 related to 100% contribution, class 2 to 95–99.9%, class 3 to 90–94.9%, class 4 to 80–89.9%, class 5 to 70–79.9%, class 6 to 50–69.9% and class 7 to lower than 50% (see Rebmann et al., 2005). The data of class 7 were disturbances enough to be not valid. Therefore, data of this class were removed.

The valid data were obtained for use after the quality control test, with the valid data accounting for 77.6, 75.4, 68.3 and 61.6%, respectively for spring, summer, autumn and winter.

2.3 Calculation schemes for surface soil heat flux

For the soil heat flux the plates were set, separately, at a 5 and 10 cm depth underground, with no device for direct measurement of surface soil heat flux (SSHF). The SSHF is an important component of surface energy balance. To remove the effect of soil heat storage, the analysis of surface energy balance and EBC features was performed not by directly utilizing the underground soil heat flux values but the surface soil heat fluxes (SSHF).

There are a range of SSHF schemes (Fuchs, 1987) and here briefly introduced are only the common methods including a combination of heat flux plate measurements and calorimetry (“PlateCal” approach, Liebenthal, 2005) and thermal diffusion equation and Correction (“TDEC” approach, Yang, 2008).

The expression for 1-D soil thermal diffusion equation is in the form

$$\frac{\partial \rho_s c_s T}{\partial t} = \frac{\partial G}{\partial z} \quad (1)$$

$$G = \lambda_s \frac{\partial T}{\partial z} \quad (2)$$

where t (s) is the time, z (m) the soil depth, T (K) the soil temperature, $\rho_s c_s$ (J kg⁻¹ K⁻¹) the soil heat capacity, λ_s (W K⁻¹ m⁻¹) the soil thermal conductivity and G (W m⁻²) the soil heat flux.

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that would result in the change of soil heat conduction coefficient leading to measurement error. Surface temperature T_0 was obtained through the conversion of longwave radiation going down- and upward, i.e., by way of

$$T_0 = \left[\left(R_{lw}^{\uparrow} - (1 - \varepsilon_g) R_{lw}^{\downarrow} \right) / (\varepsilon_g \sigma) \right]^{1/4} \quad (7)$$

5 wherein $0 < \varepsilon_g \leq 1$ is given empirically. For convenience ε_g was set to be 0.98 for the surface reflectivity, the Stefan-Boltzman constant $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, R_{lw}^{\uparrow} and R_{lw}^{\downarrow} denote, respectively, long-wave radiation going up- and downward.

(2) The TDEC scheme is utilized for gaining a reliable temperature profile to make accurate calculation of heat flux. Therefore, Yang et al. (2008) developed a new simple method to estimate soil heat flux from soil temperature and moisture observations, thereby making a reliable temperature profile from limited observations by use of linear interpolation or cubic splines.

The discrete form of Eq. (1) about the new linear interpolation method can be represented by a tridiagonal system (Eq. 8a–c).

15 For the 1st layer, $T_1 = T_{\text{sfc}}$ (8a)

For the i th layer, $A_i T_i^{t+\Delta t} = B_i T_{i+1}^{t+\Delta t} + C_i T_{i-1}^{t+\Delta t} + D_i$ (8b)

where

$$A_i = \frac{1}{2} \rho_s c_{s,i} (\Delta z_{i-1} + \Delta z_i) + \frac{\lambda_{s,i-1} \Delta t}{\Delta z_{i-1}} + \frac{\lambda_{s,i} \Delta t}{\Delta z_i}, \quad B_i = \frac{\lambda_{s,i} \Delta t}{\Delta z_i}, \quad C_i = \frac{\lambda_{s,i-1} \Delta t}{\Delta z_{i-1}},$$

$$D_i = \frac{1}{2} \rho_s c_{s,i} (\Delta z_{i-1} + \Delta z_i) T_i^t.$$

20 For the n th layer, $T_n = T_{\text{bot}}$ (8c)

in which T_{sfc} and T_{bot} represent temperature at surface and bottom level, respectively, as the boundary conditions of the equation.

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Solving Eq. (8a–c) led to a profile of soil temperature T_{TDEC} . There was deviation ΔT of the T_{TDEC} from T_{obs} . The temperature ΔT correction procedure was as follows. (1) From $\Delta T_k = T_{k,\text{obs}} - T_{k,\text{TDE}}$ we had ΔT_k , where subscript k denoted the node ($k=6$ in SACOL), $T_{k,\text{obs}}$ the measurements and $T_{k,\text{TDE}}$ the calculations from the soil thermal diffusion equation; (2) ΔT_k at node k was linearly interpolated onto all other nodes i to have the difference ΔT_i ; (3) a final soil temperature profile was acquired from $T_i = T_{i,\text{TDE}} + \Delta T_i$ for each node. If the bottom level was deep enough, the heat flux with respect to the surface thermal condition was ignored, that is, we set $G(z_{\text{ref}}) \approx 0$. And in that case, integration was performed using (4) from bottom to surface layer, resulting in layered and surface soil heat flux.

3 Analysis of surface energy balance characteristic

For the system of energy flux measured by means of the eddy covariance method, the energy balance equation is represented by $\text{LE} + \text{Hs} = R_n - G_0 - S - Q$, with LE: latent heat flux, Hs: sensible flux, R_n : net radiation and G_0 : surface soil heat flux. We made analysis of TDEC-obtained surface soil heat fluxes. As shown in Wilson et al. (2002), with a canopy height in excess of 8.0 m, the canopy heat storage (S) would exert greater effect on the energy balance closure (EBC) feature, or in other words, with the height below 8.0 m, S is ignored; Q is the total of additional energy source/sink and is generally small enough to be neglected. Hence, the surface energy equilibrium can be given as $\text{LE} + \text{Hs} = R_n - G_0$. The observations obtained so far indicated that only roughly 70 ~ 80% of the energy was in EBC, with some 30 ~ 20% as the residual denoted by $\text{Res} = R_n - \text{Hs} - \text{LE} - G_0$ for EBU.

To investigate the surface energy balance and its residual on a seasonal scale for the research region, further study was undertaken (Fig. 1a–d). And the average time is 30 min. In addition, calculation was made independently of the components of seasonal energy balance to find their portions of net radiation and their Bowen ratio (Hs/LE). As shown in Table 1, the seasonally averaged daily variation of

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these components exhibited the patterns typical of fine days. The daily variation in net radiation (R_n) was maximal (minimal) in summer (winter), with 478.7 vs. that of $\sim 268.5 \text{ W m}^{-2}$. The springtime R_n was bigger than the autumnal value (422.0 compared to 337.9 W m^{-2}). The seasonally averaged daily surface soil heat flux G_0 was the largest (smallest) in summer (winter). However, the surface soil heat flux accounted for a comparable portion of net radiation each season, ranging over $20 \sim 25\%$.

The magnitudes of sensible heat flux (Hs) were positive (negative) during the daytime (nighttime), and the seasonal mean daily maximum Hs was the highest (lowest) in spring (autumn), with its summer and winter values in between. But sensible fluxes constituted a portion of 49.4% (45.5%) of net radiation in winter (spring), showing the Hs of the two seasons to hold a predominant place. Net radiation was utilized mainly for sensible heating. The portions of net radiation taken by sensible and latent heat fluxes were comparable in summer to those in autumn. The latent heat fluxes (LE) were positive in the daytime in view of the wet summer over the loess land, causing the summer mean daily maximum LE to be highest in sharp contrast to the lowest winter value, with spring and autumn daily maxima LE in between. The nocturnal latent heat fluxes were of small positive values in all seasons but winter, suggesting weak evaporation occurring from surface but the nighttime latent heat flux approximated to zero in winter. The portion of net radiation taken by latent heat flux was 9.9% ($\sim 31.0\%$) in winter (both summer and autumn). The Bowen ratio (Hs/LE) was 5.00 (2.01) in winter (spring). The portion of net radiation taken by Hs was comparable to that by LE in summer and autumn, reaching the Bowen ratio of roughly 1.0. This occurred because the winter and spring were dry, leading to small evaporation from surface, with the energy transport dominated by sensible heat flux in the near-surface layer, in comparison to a very small part of latent heat flux transport, especially in winter. The precipitation in summer and autumn as the wet seasons there formed more than 80% of yearly total and the latent heat flux was augmented owing to the seasonal rainfall and strong evaporative ability.

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The residual part of energy balance displayed appreciable daily change, with its negative values in the night, meaning that effective energy was lower than turbulent energy while the daytime residual energy was of larger positive magnitudes suggestive that effective energy exceeded turbulent energy. The seasonal mean daily maximal residual energy occurred almost at the same time as that of net radiation in all seasons except summer, the former lagging by some 2 h in summer. The seasonal mean daily maximal residual reached 69.0, 67.7, 41.5 and 43.4 W m⁻² in summer, winter, spring and autumn, respectively. On the other hand, the portion of net radiation taken by residual energy arrived at 19.0, 7.7, 14.8 and 11.6%, respectively in winter, spring, summer and autumn. As evidenced in Fig. 1, different-degree energy imbalance happened in the night of all seasons except summer and the effective energy was a lot lower than turbulent energy in the winter night, with the residual reaching roughly -40.0 W m⁻², in comparison to almost zero in the night of summer, meaning that the EBC took place, with $R_n \approx G_0$ and $H_s \approx -LE$ implied.

4 Discussion

Based on the foregoing analysis, different-degree energy imbalance features existed on a seasonal basis for the study zone. To better understand the causes of seasonally averaged energy balance unclosure (EBU) of SACOL data, study was made of the effect on the EBC of flux contribution from the target area, low-frequency part of the turbulence spectra, turbulent mixing and diverse schemes for surface soil heat flux.

Schemes of analyzing EBC are many. On the whole, they fall into four types, consisting of least squares for linear regression coefficient (OLSs), the reduced major axis (RMA) method, moment methods (MMs) and energy closure rate (EBR), as presented in Wilson et al. (2002). This work makes an attempt to investigate EBC using the least squares scheme for finding the linear regression coefficient of turbulent energy (LE + H_s) against the independently derived available energy ($R_n - G_0$). For the OLSs scheme the idealized energy balance closure was obtained with the intercept of 0 and slope of 1.

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4.1 EBC effects of flux contribution from the target source zone

The valid data from quality control treatment were analyzed for EBC features and each of the fp_classes 1–6 data retained (Sect. 2.2) was utilized to examine its impact on EBC feature. Figure 2 delineates the relation of the seasonal flux contribution to EBC (denoted by OLS slope), showing that the bigger the percentage contribution, the smaller the effect of the underlying surface features on the data and the closer the data to an idealized state (Rebmann et al., 2005). Also, from the figure, we see that when the percentage contribution increased, so did the OLS slope. In spring the EBC (OLS slope) of the 6-categories, each arrived at >50%, and for >80% flux contribution, the OLS slope exceeded 0.600 and for 100% the slope was 0.926; in summer the smallest OLS slope was <0.600 for fp_class 4 data but nevertheless no effect occurred on bettering OLS slope as a function of increased flux contribution. When summer flux contribution reached 100%, the OLS slope was 0.833, considerably lower than the spring counterpart, with ~20% of the energy in EBU, suggesting that the EBC impact of other factors was great in summer. The autumnal OLS slope increased significantly with augmented flux contribution rate, leading to >0.500 (0.900) slope for the >70% (100%) contribution. In winter with >80% (100%) flux contribution, the OLS slope reached only 0.439 (~0.660).

Our study shows that EBC became the better, the greater the surface flux contribution in percentage, which was, however, under the effect of observational height, surface roughness, boundary layer characteristics and atmospheric stability. Therefore, we performed an intensive research into the percentage turbulent flux contributions in a range of wind directions and stability z/L (where z is the aerodynamic measured height and L the Monin-Obukhov length) so as to reveal the optimal portion of the target zone for idealized energy balance.

Table 2 presents the 2006–2010 mean percentage contribution over eddy covariance fluxes in differing wind directions and z/L , with the flux contribution in percentage lower than 50% removed. It is clear that for $z/L < -0.2$, the turbulent flux contributions in all directions but the due north averaged over the target zone exceeded 97%; at

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$-0.2 \leq z/L < -0.0625$ the percentage contributions arrived at $>90\%$ in all directions, even in excess of 95% in some directions; with $-0.0625 \leq z/L < 0.0625$, the contributions exceeded 80% for all directions; in $0.0625 \leq z/L < 0.2$ the contributions for all directions were higher than 70% , a major part of the flux contribution exceeding 80% ; at $z/L \geq 0.2$ these contributions were a great deal smaller in all wind directions. This indicated that with increased atmospheric stability, all-direction flux contributions exhibited reducing trends, with maximal (minimal) contribution in intense instability (strong stability). Southeasterly (SE) wind prevailed over the loess plateau all the year round, next being northwest wind (NW), with flux contribution being higher in the latter case. Particularly in the strong atmospheric stability the contribution in the SE wind was 63% alone. In a similar way we analyzed the seasonal flux contributions in a range of z/L and wind directions in agreement, on the whole, with the above.

4.2 EBC effect of the low-frequency part of turbulence spectra

The high- and low-frequency parts of the spectra each had impact on EBC. Foken et al. (2006) came to the conclusion that the EBC was in a closer relation to the low-frequency part. Thus, we made analysis of the EBC impact of the low-frequency portion from the SACOL measurements. Usually, 30-min average time data were applied to turbulent flux analysis. Because of the heterogeneous surface and large-scale turbulent flux it was not likely to include all turbulence spectra in the 30-min time period. Therefore, it was necessary to re-determine the average time length for all turbulent fluxes to have their low-frequency parts included. Following Moncrieff et al. (2005), it was recommended to use the Ogive function as a most ideal method for selecting an average time length for any station dataset.

Ogive function is for the cumulative integral of the cospectrum starting with the highest frequencies. Whether the Ogive curve reaches the asymptotic line is a criterion, by which we determine if enough samples are obtained that capture all frequencies, with the function expressed as

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$$\text{Og}_{w,x}(f) = \int_{f_{\text{high}}}^f \text{Co}_{w,x}(f) df \quad (9)$$

where $\text{Co}_{w,x}$ is the cospectrum of turbulent flux, with w as the vertical wind component and x the horizontal wind component or scalar; f_{high} is the Nyquist frequency; f the frequency larger than the lowest resolution $f_{\text{low}} = (2T)^{-1}$; T is the timeseries length. To improve the statistical significance we selected the time sequences 4 h spaced for analysis, i.e., the series of frequencies higher than approx. 6.9×10^{-6} Hz. In doing so, the sequences not only contained the low-frequency turbulence spectra produced by intermittent fluxes but avoided at the same time the loss of partial information due to flux changing diurnally as well.

Foken et al. (2006) defined the Ogive function in a different way, leading to 3 definitions or cases, as illustrated in Table 3. Case 1 (Definition 1) is for an idealized convergence, reaching a set value before the 30 min integral is finished from high to low frequency part, permitting a 10% error to be between the set value and largest Ogive value. If the condition is fulfilled, then all spectra are contained, on the whole, in the time interval such that the 30-min average period can be used to assess the turbulent flux effectively. In Case 2 the function produces an extreme value during its integration followed by the Ogive value decreasing. In Case 3 the Ogive value keeps growing without any steady magnitude appearing, which is the principal cause of loss of flux (Finnigan et al., 2003). This means that in Cases 2 and 3 the function is non-convergent, suggesting that the scheme of 30 min turbulent fluxes in common use is unable to make assessment of the turbulence feature.

Ogive test has to be based upon a no-data-lacking time sequence. A new time-series always contains non-steady-state elements that have appreciable effect on data quality such that a conditional test has to be conducted of the sequence. The 2006–2010 series was divided into those of 4 h length, with the sequences removed that had observation missing data, and unphysical conditions and spike as well as the non-steady sequences eliminated that were unable to pass the steady-state test. Then,

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the seasonal sequences were examined in detail, indicating that there were 1147 (1310) samples of spring vapor (temperature) covariance $\overline{w'q'}$ ($\overline{w'T'}$), 1182 (1319) samples of summer $\overline{w'q'}$ ($\overline{w'T'}$); 1257 (1423) samples of autumnal $\overline{w'q'}$ ($\overline{w'T'}$); 1184 (1403) samples of winter $\overline{w'q'}$ ($\overline{w'T'}$) meeting the conditions taken for the Ogive analysis. The results were shown in Table 4. For the Ogive-analysis temperature covariance (Og_{wT}) characterizing the Ogive-treated sensible heat flux, samples satisfying Case 1 prevailed for all the seasons, with >75% of the ogives showing the convergent curve in spring and summer compared to about 70% (60.3%) in autumn (winter). For Og_{wT} , the samples meeting the needs of both Cases 2 and 3 made up >10% of the tested series on a seasonal basis, with the portion higher in Case 2 than in Case 3 except spring samples. Further examination showed that the non-convergent Ogive function curve of temperature covariance ($\overline{w'T'}$) occurred typically in the evening and nighttime, mostly in the midnight and around sunrise when sensible heat fluxes were negative and the mean temperature was low. According to the Ogive function analyzed water covariance Og_{wq} characterizing the Ogive-treated latent heat flux, the seasonal portions of latent heat flux samples satisfying Cases 1–3 were much lower compared to those of the sensible heat flux in the same season. The portion of samples meeting the requirement averaged ~55.0% in all seasons but winter (42.0%), suggestive that the latent heat flux was greatly underestimated, a possible cause that gave rise to the energy balance unclosure (EBU) in winter. The winter non-convergent Ogive function curve generally took place in the night when atmospheric stratification was stable in addition to the daily relative humidity changing in the vicinity of its extreme-value point that was in its extremely unstable state. The seasonal sensible and latent heat fluxes were possibly underestimated to different extent, implying that the EBC effect of low-frequency part differed, with minimal effect in spring and summer, next being in autumn, and maximal effect in winter. We discovered bigger EBU effect of latent than sensible heat flux. As a result, for the SACOL data the 30-min average length was able to reflect the turbulent flux properties, on the whole. Of course, some large-scale eddy fluxes were underestimated.

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4.3 EBC impact of turbulent mixing

Factors influencing EBC are many, among which is turbulent mixing that has prominent effect. To investigate the relation of turbulent mixing to EBC, we define

$$RI_w = \frac{\sqrt{w'^2}}{\sqrt{w'^2 + \bar{U}}} \quad (10)$$

5 as a factor characterizing the turbulent mixing, and in Eq. (10) \bar{U} denotes the horizontal mean wind, whereby too strong turbulence was avoided in the case of too weak wind, and the higher the RI_w , the fuller the mixing. Besides, the observations were separated into two parts, one for the daytime and the other for nighttime. The positive and negative net radiation ($R_n > 0$ and $R_n \leq 0$, respectively) was set to be in the daytime and
10 nighttime. Then, the data at the two intervals were classified into 10 equal portions, each accounting for 10% of the total data to explore the relationship between OLS slope and RI_w .

Figure 3 depicts the RI_w -OLS slope relation during the day and night in all the seasons, showing that the EBC feature was better by day than by night, with daytime OLS slope enlarged appreciably as a function of increasing RI_w . In spring (Fig. 3a) the daytime EBC was good, with ~ 0.600 of the OLS slope at low RI_w and the slope increased markedly with the augmented RI_w , reaching ~ 0.800 at $RI_w = 0.120$, followed by the OLS starting to increase slowly with RI_w , arriving at roughly 0.900 of OLS slope for EBC at high RI_w . In spring the nighttime slope increased fast as a function of RI_w , but the nocturnal turbulence was weak, causing RI_w to be much weaker compared to the daytime counterpart. In summer (Fig. 3b) the RI_w -varying OLS slope in the daytime was the same as the springtime counterpart; at $RI_w = 0.147$ the slope was about 0.800, followed by its slow growth as a function of RI_w , and at high RI_w the slope was 0.830 for 83% of the energy involved in EBC. In the summer night the slope was less than 0.400
20 at low RI_w ; for $RI_w = 0.074$ the slope was 0.540, followed by its sudden drop, and the

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slope was 0.450 at $RI_w = 0.086$, followed by its continued growth as a function of RI_w . In autumn (Fig. 3c) the RI_w -dependent daytime OLS slope was mitigated compared to the springtime pattern, with the slope reaching about 0.6 at low RI_w , and with RI_w increased to 0.160, the slope was approximately 0.800, followed by the slow growth of the slope with intensified turbulent mixing. In the night, the slope was correspondingly enlarged as RI_w increased. In winter (Fig. 3d) only $\sim 45.0\%$ of the energy was in daytime EBC at low RI_w and as RI_w increased, so did the slope at rapidity and the slope was maintained mainly at ~ 0.600 at $RI_w = 0.167$. During the winter night no significant trend of RI_w -dependent OLS slope was observed but the trend was the same as the nighttime trend in summer. It follows that when turbulent mixing attained certain strength, the EBC arrived at its optimal state and became stabilized. Because of other influencing factors available an identical turbulent mixing vigor caused the EBC to be better during the day than the night.

4.4 EBC effect of calculated surface soil heat flux

Since the direct observation of surface soil heat flux (SSHF) was not carried out in most of the experiments, SSHF made up only $\sim 20\text{--}25\%$ of the energy for surface energy balance, as was given in Sect. 3, and this part of energy, although small, served as an important component thereof. As a consequence, the scheme for calculating SSHF and its accuracy deserve our particular attention, which is likely to directly affect the surface EBC. The schemes introduced in Sect. 2.3 were utilized to investigate the EBC impact of calculated SSHF.

We compared the EBC effect of soil heat flux, 5 cm deep in soil to that of the PlateCal and TDEC-calculated SSHF on a seasonal basis, as shown in Table 5. The table shows the EBC was marked by strong seasonality, with EBC dropping from spring to winter, in order. The direct use of the 5-cm-layer soil heat flux in EBC analysis indicated $>30\%$ of the energy in EBU and the use of PlateCal calculated SSHF in lieu of the plate-measured heat flux resulted in different-degree seasonal EBC improvement, with the increase by 11.1, 9.6, 10.4 and 7.7%, respectively for spring, summer, autumn

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and winter and the TDEC obtained SSHF utilized in EBC analysis showed 82.7% of the energy in EBC in spring (5.2% higher compared to the PlateCal value), and 78.7 and 75.5% in summer and autumn, respectively, which were improved somewhat in comparison to the PlateCal calculations, except the winter case, whose retrieval was poorer in comparison. It follows that different schemes for SSHF calculation made considerable impact on EBC, and the EBC impact of the different schemes varied in differing seasons. Hence, a more accurate scheme of SSHF will improve the EBC study in an effective manner.

5 Conclusions

Based on the 2006–2010 SACOL eddy covariance, an intensive study is conducted of the seasonal energy balance, and the EBC effect of the flux contribution from the target zone, low-frequency part of the turbulence spectra, turbulent mixing strength and SSHF calculations. We come to the following conclusions.

(1) Through strict quality analysis and control of the SACOL eddy covariance by way of SST, ITC test and footprint analysis we have obtained valid data of 77.6, 75.4, 68.3 and 61.6% of seasonal total for spring, summer, autumn and winter, respectively. Evidently, the spring data quality is optimal.

(2) The energy balance over the semi-arid loess plateau is marked by appreciable seasonality. The Bowen ratio there is 5.00 and 2.01 in winter and spring, respectively, with the Bowen ratio of ~ 1.0 for summer and autumn. The seasonal SSHF is on the order of 20–25% of net radiation. The portion of residual is 19.0, 14.8, 11.6 and 7.7% of net radiation, in order, for winter, summer, autumn and spring.

(3) To investigate the EBU feature in the semi-arid climate, research is performed into the EBC effect of the flux contribution from the target zone, the low-frequency part of the turbulence spectra, turbulent intensity and SSHF calculations. The percentage contribution of turbulent flux declines as a function of increasing atmospheric stability and for SACOL observations the flux contribution in percentage is higher in the sub-prevailing

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NW than the predominant SE wind. As the flux contribution grows, the OLS slope increases correspondingly but even the contribution in percentage reaches 100% the energy balance fails to be completely closed, and especially in winter the OLS slope is approximately 0.660 in sharp contrast to the >0.900 for the slope in spring and autumn.

The Ogive analysis succeeds in assessing the EBC effect of the low-frequency turbulent flux, indicating that the relatively smaller impact occurs in spring and summer, with the maximal effect in winter, and, besides, the portion of underestimated latent heat fluxes is much larger compared to that of the underestimated sensible heat flux, implying that the major part of energy in EBU is attributed to the underestimated latent heat flux. Evidently, latent heat flux makes greater impact on EBC than the sensible counterpart. When turbulent mixing arrives at certain strength, the EBC reaches its optimal stage and becomes stabilized. In spring, with RI_w (Eq. 10) being 0.120, the EBC starts to be stabilized and at $RI_w = 0.147, 0.160$ and 0.167 for summer, autumn and winter, respectively, the EBC feature becomes stabilized. But due to other factors the EBC is better in the daytime than the nighttime even at the same RI_w . The diverse SSHF schemes differ in influencing EBC feature and in making seasonal EBC improved at different degrees. The EBC from TDEC calculated SSHF is superior to that from the PlateCal counterpart in all the seasons except winter. The winter EBC from the former case is worse than that from the latter.

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Table 1. Seasonal portion of net radiation (%) taken by the components of surface energy balance and the Bowen ratio over the semi-arid loess plateau.

	H_s/R_n (%)	LE/R_n (%)	G_0/R_n (%)	Res/R_n (%)	H_s/LE
Spring	45.5	22.6	24.2	7.7	2.01
Summer	32.7	31.5	21.0	14.8	1.04
Autumn	32.0	31.6	24.8	11.6	1.01
Winter	49.5	9.9	21.7	19.0	5.00

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Table 2. Eddy covariance flux contribution (%) from the target zone.

	Wind direction (°)															
	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
<i>z/L</i>																
A	92	99	99	99	99	98	98	98	97	98	98	99	97	98	99	99
B	98	96	97	94	97	95	94	95	96	95	95	94	91	95	97	98
C	89	90	90	88	89	83	84	87	90	87	87	86	83	90	94	92
D	80	81	83	83	84	73	73	79	85	80	80	79	73	78	85	83
E	70	71	74	73	70	64	63	65	70	66	70	69	65	66	76	71

Notes: case A stands for $z/L \leq -0.2$; B for $-0.2 < z/L \leq -0.0625$; C for $-0.0625 < z/L \leq 0.0625$; D for $0.0625 < z/L \leq 0.2$ and E for $z/L > 0.2$.

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Table 3. Definition of three different cases for the behavior of ogive functions (Foken, 2006).

Case	Criterion
(1) Convergent ogives within the 30 min interval	$\frac{ \text{Og}(150 \text{ min}) }{\max \text{Og} } > 0.9$ and $\frac{ \text{Og}(30 \text{ min}) }{\max \text{Og} } > 0.9$
(2) Ogives with a distinct extreme value before a 150 min integration time	$\frac{ \text{Og}(150 \text{ min}) }{\max \text{Og} } \leq 0.9$
(3) Not convergent ogive even for 150 min	$\frac{ \text{Og}(30 \text{ min}) }{\max \text{Og} } \leq 0.9$ and $\frac{ \text{Og}(150 \text{ min}) }{\max \text{Og} } > 0.9$

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Table 4. Ogive function analysis of seasonal sensible (Og_{wq}) and latent (Og_{wT}) heat fluxes from SACOL data.

	Spring (%)			Summer (%)			Autumn (%)			Winter (%)		
	Case1	Case2	Case3									
Og_{wq}	56.0	25.0	19.0	54.5	27.4	18.1	56.7	26.2	17.1	42.0	39.8	18.2
Og_{wT}	77.7	10.2	12.1	75.4	13.2	11.4	69.4	16.2	14.3	60.3	23.2	16.5

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Table 5. Energy balance closure from 5-cm-depth soil heat flux vs. surface soil heat flux.

	$(LE+Hs)/(R_n - G_{-5\text{cm}})$			$(LE+Hs)/(R_n - G_{0,\text{PlateCal}})$			$(LE+Hs)/(R_n - G_{0,\text{TDEC}})$		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Spring	0.664	25.61	0.914	0.775	17.31	0.916	0.827	11.7	0.909
Summer	0.645	21.2	0.915	0.741	11.53	0.909	0.787	4.06	0.906
Autumn	0.619	17.19	0.909	0.723	12.26	0.902	0.755	12.4	0.9
Winter	0.554	17.05	0.895	0.631	16.13	0.868	0.607	18.72	0.848

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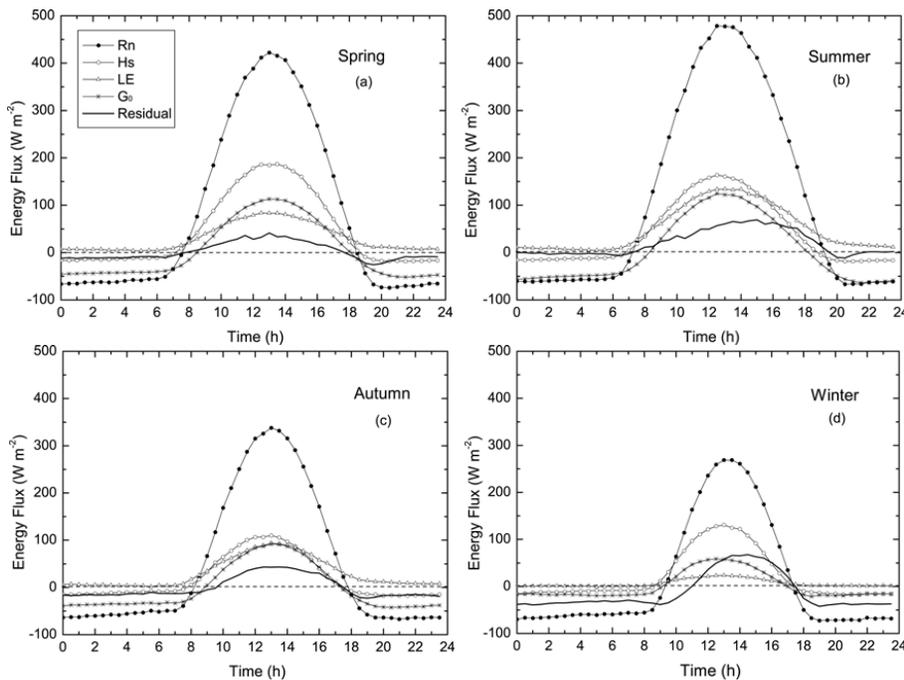


Fig. 1. Seasonally averaged daily change in the components of energy balance over the semi-arid loess plateau.

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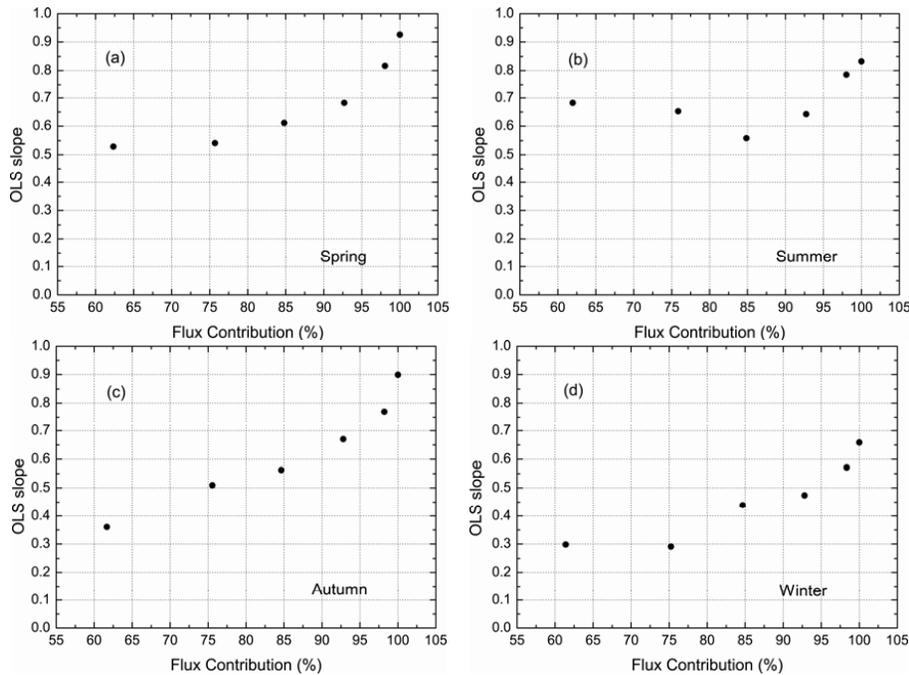


Fig. 2. Seasonal effect of flux contribution from the target zone on energy balance closure denoted as OLS slope in the target zone.

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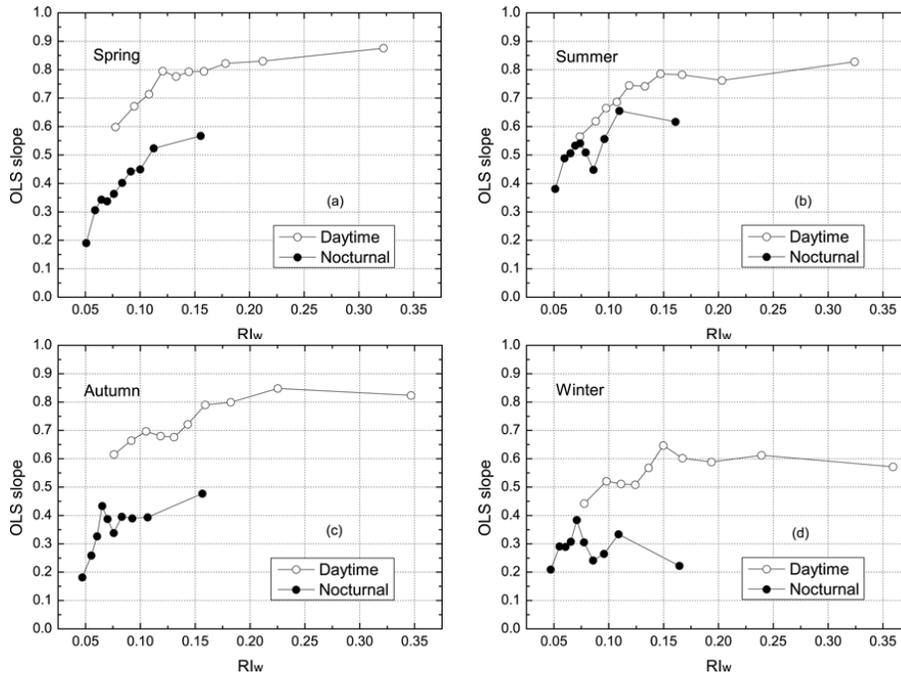


Fig. 3. As in Fig. 2 but for turbulent mixing intensity.

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