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Turbulent exchange of CO₂ over a broadleaf-Korean pine forest in Changbai Mountain, northeast China

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Abstract Turbulent exchange of CO₂ was measured continuously via the open-path eddy covariance technique over a broadleaf-Korean pine forest in Changbai Mountain, northeast China. The results show that with near-neutral atmospheric stratification, CO₂ and vertical wind components measured over the forest canopy in the inertial sub-range followed the expected $-2/3$ power law. The dominant vertical eddy scale was about 100 m. The frequency ranges of eddy contributions to CO₂ fluxes were mostly within 0.01–2.0 Hz. Large eddies with low frequency over the canopy contributed more to CO₂ fluxes than small eddies. The open-path eddy covariance system could satisfy the estimation of turbulent fluxes over the canopy, but the CO₂ fluxes between forest and atmosphere were generally underestimated at night because of the increment non-turbulent processes, suggesting that the CO₂ fluxes estimated under weak turbulence need to be revised correspondingly.

Keywords broadleaf-Korean pine forest, eddy covariance method, CO₂ flux, turbulent exchange

1 Introduction

The evidence is now overwhelming that much of global warming is caused by major human-made greenhouse gases, mainly in the form of CO₂ (Chai et al., 2004). Consequently, carbon exchange between the biosphere and the atmosphere has been all along an important

subject in the research on global change (Huang, 2002; Yu et al., 2005). In the last 30 years, a large number of studies using various methods (e.g., remote sensing, forest inventory, atmospheric inversion models, micro-meteorological techniques and chamber measurements) have been conducted, in size ranging from small sample plots to areas on a regional scale.

The eddy covariance method, a micro-meteorological technique, has been widely applied to measure mass and energy fluxes to and from terrestrial ecosystems. It is considered the standard tool in carbon budget studies within the FLUXNET community, for it provides a direct and continuous measure of net carbon and water fluxes across the spectrum of time with high resolution. In China, studies of CO₂ budget via the eddy covariance technique are at a highly developed stage and over 40 field eddy flux sites, including forest, farmland, wetland and grassland, are now in operation. Some primary results about seasonal, annual and inter-annual carbon budget and their controlling factors have been reported (Guan et al., 2005; Zhou et al., 2004). However, as yet few studies have been carried out concerning the turbulent processes of CO₂ exchange at the interface of vegetation and atmosphere.

As a micro-meteorological technique, the environmental conditions to be met for application of eddy covariance method require large homogeneous flat sites, with an adequate and representative range (Wen et al., 2005). In addition, a well-developed turbulence is very desirable. Under stable stratification, the high frequency eddies typically up to 10 Hz always dominate the measured fluxes. The size of the smallest eddy in atmospheric flows is smaller than 1 mm. Assuming that the vertical wind speed is 0.5 m/s, the corresponding frequency response of the sensor should be at least 500 Hz in order to capture this eddy motion. However, for most instruments, including infrared gas analyzers and sonic anemometers, their frequency response is much lower than that. It is therefore inevitable that we miss observations of high frequency signals which could cause a systematical underestimation of turbulent fluxes when eddy covariance measurements are conducted during the night, under

Translated from *Chinese Journal of Applied Ecology*, 2007, 18(5): 951–956 [译自: 应用生态学报]

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conditions of stable stratification. We trust that our study of turbulent exchange characteristics over vegetation, particularly over canopy with tall plants, will help to deepen understanding of biophysical processes of carbon exchange between terrestrial ecosystems and the atmosphere. Additionally, our study results could provide important evidence for further data quality assurance and quality control (QA/QC).

The Changbai Mountain forest flux site is one of the ChinaFlux sites. It is an ideal place to carry out studies of CO₂ exchange between forest and atmosphere by micrometeorological techniques, for the terrain surrounding the eddy tower is flat and homogeneous. In our investigation, the turbulent exchange characteristics of CO₂ were examined based on the measurement of an open-path eddy covariance system. The results will contribute to a better understanding of the biophysical processes of carbon budget and can help in data QA/QC at forest flux sites.

2 Study area and methods

2.1 Site description

The experimental site is located within the National Natural Conservation Park of Changbai Mountain, northeastern China (42°24'N, 128°6'E, elevation 738 m). The terrain surrounding the tower is ideally flat with a range >5000 m southwest. The site is classified as having a dark brown forest soil, with a mixed stand of Korean pine (*Pinus koraiensis*) over 300 years old, interspersed with Tuan linden (*Tilia amurensis*), larch (*Larix olgensis*var), Mono maple (*Acer mimo*) and other deciduous species. The mean canopy height is about 26 m, stand density is 560 stems/hm² (stem diameter >8 cm) and the maximum leaf area index is up to 6.0 m²/m².

2.2 Methods

2.2.1 Turbulent flux measurements

One set of open-path eddy covariance system was mounted on the 62 m high meteorological tower. The sensors were placed on a boom located 40 m (one and half tree height) above the ground and extending 3 m upwind of the tower to minimize flow distortion caused by the structure of the tower. Wind velocity and virtual temperature fluctuations were measured with a three-dimensional sonic anemometer (CSAT3, Campbell Inc., USA). CO₂ concentration fluctuations were measured with a fast response open-path, infrared gas analyzer (Li-7500, Li-Cor Inc., USA). The sensors responded to frequencies up to 10 Hz.

Ancillary meteorological elements were measured concurrently and routinely by automatic weather stations.

The sensors for the ancillary measurement responded to frequencies up to 0.5 Hz. To coincide with the flux measurements, 30-min averages were stored in a data logger (CR5000, Campbell Inc., USA). Additionally, a seven-level (2.5, 8, 22, 26, 32, 50 and 60 m) CO₂ concentration profile system was established to measure the spatial distribution of CO₂.

2.2.2 Data processes

The CO₂ fluxes (F_c) were computed at 30-min intervals with the mean covariance between vertical velocity (w') and CO₂ concentration (c') fluctuations according to 'Reynolds' decomposition, i.e., $F_c = \overline{w'c'}$. The primes indicate deviation from mean values, and the bar over the product denotes the average over time. Positive flux densities represent CO₂ transfers away from the surface and negative values denote the reverse. Post-processing of the flux data include linear detrending, sonic anemometer tilt correction, and correction for the fluctuations of water density. To compensate for the underestimation caused by frequency response limitations when the air becomes stable under stratified conditions during the night, spectral correction were applied to retrieve the underestimation. More details about the data correction processes are presented by Wu et al. (2004). Data calculation and plotting were carried out by using the package of Matlab 6.5 (MathWorks Inc., USA).

3 Results and discussion

3.1 Vertical wind velocity and CO₂ concentration

There are numerous rotating eddies within the airflow over the vegetation surface when turbulence is well developed. Each eddy moves a parcel of air with different CO₂ concentration, temperature and humidity. CO₂ is transferred to and from the interface of the forest and atmosphere through the vertical movements of the eddies. Figure 1 shows a typical time series of instantaneous turbulent fluctuations in 10 s over a canopy measured during midday during the growing season. It can be seen that both CO₂ concentration and vertical wind velocity demonstrated a highly variable and irregular pattern of fluctuation. In the case of CO₂, the maximum amplitude of its concentration was up to 2 mg/m³ within 10 s, and the change in CO₂ concentration even managed to reach 1 mg/m³ within 1 s. This suggests the necessity of using 10 Hz or even higher frequency-response sensors to capture the fluctuations of small eddies (Moore, 1996). In addition, although eddy motions are stochastic, the CO₂ concentration within the upward eddies (called positive vertical wind velocity) was generally lower than that within the downward eddies (called negative vertical wind

velocity), due to the CO₂ uptake through photosynthesis. Similarly, measured data from the 7-level CO₂ concentration profile system also demonstrated that at daytime the CO₂ concentrations below the eddy covariance system were much lower compared to the ambient CO₂ background concentration, with the minimum observed at the canopy surface. At nighttime, the trend is reversed due to the CO₂ emission from vegetation and soil respiration. The CO₂ concentration differences between the vertical eddies is the physical basis of CO₂ flux measurements at a given height over the forest canopy via the complex eddy covariance technique.

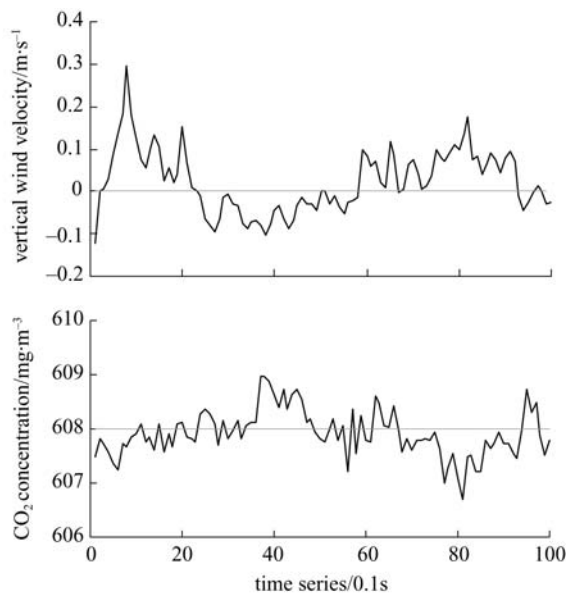


Fig. 1 Time series of instantaneous turbulent fluctuation above canopy during midday of the growing season in 10 seconds

3.2 Characteristics of turbulence spectra

Power spectra describe the amplitude of instantaneous fluctuations over different frequency ranges, while co-spectra describe the flux contributions from different eddy scales. In order to examine the frequency response performance of open-path eddy covariance system to the high frequency turbulent signals, as well as the physical structure of turbulence for CO₂ exchange over the canopy, spectra and co-spectrum analyses were carried out on the measured raw data. The spectra and co-spectrum were determined with a time series analysis, with the linear trend removed, using the Welch averaged periodogram method. The power spectra were normalized by the variance of the corresponding time series and the co-spectrum was normalized by the covariance (absolute value) of the two corresponding time series. Both spectra, multiplied by natural frequencies, are plotted against natural frequency.

The peak and slope of each spectrum are the two most important features which characterize their structures. In

the surface boundary layer, the normalized power spectra shapes exhibit universal characteristics, assuming that the small-scale turbulence structure is isotropic. In the inertial sub-range the spectra follow the surface layer similarity theory. The power spectra generally decrease linearly with a slope of $-2/3$ in the inertial sub-range according to Kolmogorov's law (Kaimal et al., 1972). In this range, the energy is transported from a low to a high frequency wave number without energy dissipation. The performance of the frequency response to turbulent motions above the forest canopy can be evaluated according to the measured turbulence behavior of the spectra in the inertial sub-range.

Figure 2 shows the power spectra of vertical wind velocity and CO₂ in the near-neutral atmosphere boundary layer measured at 13:00 on September 17, 2003. It can be seen that spectral similarity exists between these two quantities under near-neutral conditions in these double logarithmic plots, and both roughly follow the $-2/3$ slope in the inertial sub-range frequency from 0.01–10 Hz. These results agree quite well with those of Kaimal's studies (Kaimal et al., 1972), suggesting that the frequency response of both the Li7500 infrared gas analyser and the CSAT3 sonic anemometer are not limiting factors in the measure of CO₂ and vertical wind velocity fluctuations. The up-tilted tail appearing in the high frequency range of the signal (frequencies >2 Hz), as measured by the Li7500 infrared gas analyzer, is to be noted. This could have been caused by the noise of the instrument, which has been experienced by several Li-Cor users (e.g. Grelle and Lindroth, 1996). Considering that the appearance of noise is assumed to be stochastic and not associated with vertical wind velocity nor with the short range of high frequency signals, its impact on flux measurement is negligible (Wen et al., 2004). This phenomenon also suggests that the wave disturbance on the turbulent measurement is weak in the Changbai Mountain forest flux site.

Figure 2 presents a clear spectrum peak for both CO₂ and vertical wind velocity. The spectral maximum (f_m) of the CO₂ data series appeared at a frequency between 0.01 and 0.02 Hz, while f_m appeared at around 0.02 Hz for vertical wind velocity. Based on the concurrently measured mean wind speed ($u = 2.0$ m/s) and the zero plane displacement ($d = 19.5$ m) reported by Liu et al. (1997), the maximum dimensionless frequency was calculated to be 0.2 ($f = n(Z - d)/u$, where n is the natural frequency and Z observation height). The dominant eddy scale L_m was calculated to be 100 m ($L_m = (Z - d)/f_m$). The maximum dimensionless frequency for the eddy over the forest canopy was relatively low compared to that of other landscape types. For example, a value of 0.4 was reported for the vertical wind velocity spectrum over a cropland (Yu et al., 2001) and 0.6 over a sea surface (Ma et al., 1997). This indicates that there are more low-frequency eddies over forest canopies and hence larger eddies dominate the turbulent exchange than other sites with low vegetation.

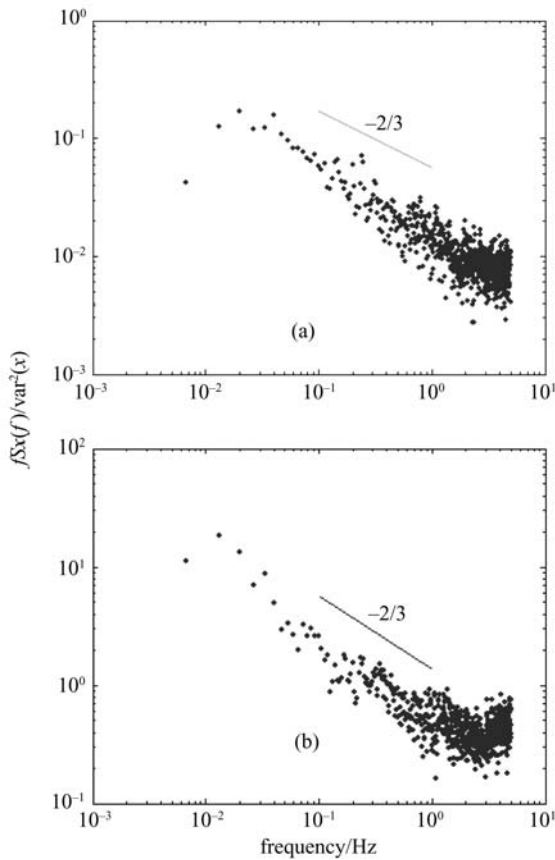


Fig. 2 Frequency weighted power spectra normalized by total variance and plotted as a function of frequency (Hz) measured by open-path eddy covariance system at 13:00 of September 17, 2003; (a) vertical wind velocity, (b) CO₂ concentration

Figure 2 also shows that the starting frequency of the inertial sub-range for vertical wind velocity spectrum was around 0.04 Hz, different from that of the CO₂ series (0.02 Hz).

Mathematically, the measured turbulent flux is the integral of a co-spectrum. The frequency distribution of the co-spectra demonstrates the contribution of eddies to the total flux at different scales (Stull, 1988; Kaimal and Finnigan, 1994). For the co-spectrum of the vertical wind velocity w and CO₂ concentration c , the integral of each co-spectrum is directly proportional to the covariance of w and c . Based on this, the magnitude of the contribution of eddies to measured fluxes in different frequency ranges can be inferred. With the semi-logarithmic graph in Fig. 3, it can be seen that small CO₂ fluxes came from the small eddies with frequencies >2 Hz. The dominant flux contributors were eddies with frequencies between 0.01–2 Hz, which is generally consistent with the above analysis of power spectra of w and c . This result suggests that the underestimation of CO₂ fluxes by the open-path eddy covariance system, consisting largely of the Li7500 infrared gas analyzer and the CSAT3 sonic anemometer, is not the main reason of flux underestimation under

near-neutral and stable atmospheric conditions, although frequency response limitation and sensor separation are always inevitable (Aubinet et al., 2000). The most probable reason for this is the rough underlying surface of the forest canopy. A similar study at a site with tall trees also revealed that low frequency eddies dominate the CO₂ flux between forest and atmosphere (Lee, 1998).

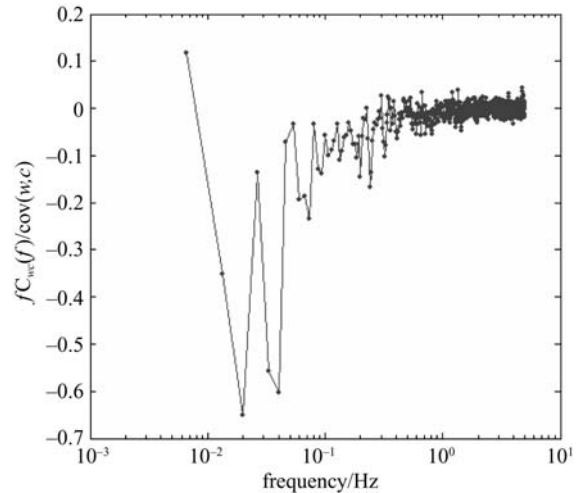


Fig. 3 Frequency-weighted co-spectrum of vertical wind velocity and CO₂ concentration measured by open-path eddy covariance system and plotted against frequency at 13:00 of September 17, 2003

3.3 Characteristics of CO₂ fluxes

The net ecosystem exchange of CO₂ between forest ecosystem and atmosphere is the sum of flux components including canopy photosynthesis and respiration of the soil, plants and woody debris. A large number of studies suggest that thermal and water conditions are the two dominant controlling factors of nocturnal ecosystem respiration. In the case of our forest site, a positive exponential relationship was reported between ecosystem respiration and soil temperature (Wu et al., 2006). Therefore, considering that there are few variations of thermal and water environment in the short time interval, the biophysical processes of carbon sources or sinks should also be relatively stable. However, the measured nocturnal data (one hour before sunset and one hour after sunrise) over the Korean pine forest showed that the magnitude of CO₂ fluxes varied considerably, with the maximum up to 0.78 mg CO₂/(m²·s) and the minimum not more than 0.01 mg CO₂/(m²·s), as can be seen from Fig. 4.

The friction velocity u^* that describes the intensity of turbulent shows a similar trend with that of the CO₂ flux on a daily basis. As shown in Fig. 4, the magnitude of CO₂ decreased with declining u^* values. For example, during night time on August 18–19, 2004, the maximum u^* value was not higher than 0.2 m/s before sunrise, the concurrently measured CO₂ fluxes were also within its low value range. Similarly, from 2:00–4:00 on August 20, 2004, the

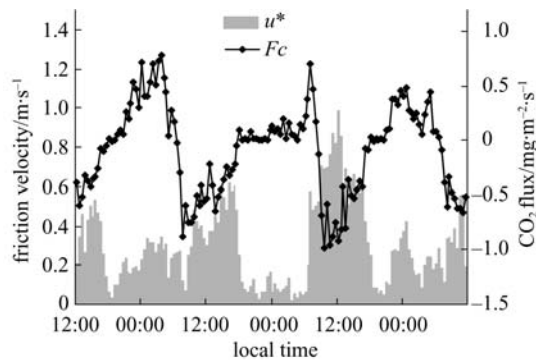


Fig. 4 Diurnal courses of friction velocity and CO₂ fluxes during August 17–20, 2004

weak turbulent as indicated by low values of u^* corresponded to low CO₂ fluxes. However, ancillary soil measurements during August 17–20, 2004 showed that there was almost no change of soil moisture at 5 and 20 cm depths and the amplitude of soil temperature fluctuations was not more than 2°C. Considering the dependence of soil respiration on the thermal and water conditions, the variations of soil respiration were expected to be small, while the measured CO₂ fluxes showed one order of magnitude variation. Figure 5 further indicates that at nighttime, the variations of measured CO₂ flux is closely related to the u^* values. It was considerably underestimated when $u^* < 0.2$ m/s, while at daytime, no significant correlation was found between these two variables.

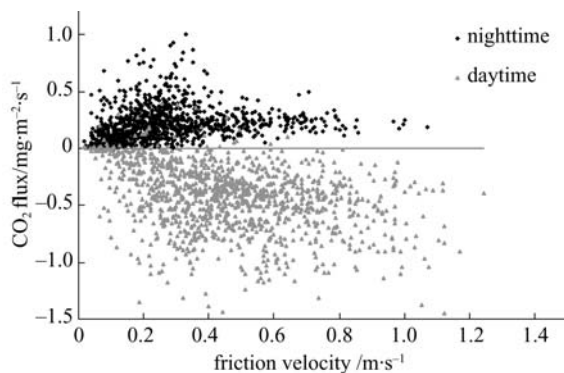


Fig. 5 Relationship of CO₂ fluxes and friction velocity in July and August 2004

It is worthy to note that at nighttime, the CO₂ flux increased with increasing u^* values when $u^* < 0.2$ m/s, and reached its maximum when u^* was within 0.2–0.4 m/s; but, when u^* increased again, CO₂ fluxes increased to an asymptotic maximum of around 0.3 mg CO₂/(m²·s). According to Figs. 4 and 5, the measured CO₂ fluxes were highly dependent on the stability of the atmosphere during the night. With wind speed increasing at sunrise, CO₂ fluxes quickly increased as a sudden outburst of accumulated CO₂ below the canopy. For example, the u^* values were very low from 21:30–23:30

on August 27, 2003. A quick emission of CO₂ occurred when u^* increased moderately, but exceeded its threshold of 0.2 m/s (Guan et al., 2005) at 0:00 o'clock. This caused a sudden increase of measured CO₂ fluxes that could not be explained by the biophysical variations of plants and soil (Wu et al., 2005).

According to the mass conservation and the continuity equations of a scalar constituent with the atmosphere, when no divergence of horizontal eddy flux exists and no horizontal advection occurs, the magnitude of the CO₂ flux over a forest is controlled by the photosynthetic performance of the canopy, the respiration rates of soil, plants and woody debris, and also by the variations of CO₂ storage term below the sensor. The last term can be quantified by the change in CO₂ concentration. Figure 6 presents the spatial-temporal evolution of CO₂ concentration in the forest during August 19–20, 2004. It can be seen that the CO₂ usually reached its maximum in the early morning, around 4:00–5:00, right before sunrise and the destruction of the thermal inversion layer. During the hour between 5:00–6:00, the CO₂ concentration reduced rapidly at all the levels, with an average reduction of up to 30 μmol/mol, demonstrating that a sudden CO₂ emission occurred in the forest. After that, the concentration decreased continuously from 8:00 to 16:00. The CO₂ concentration gradients were rather small during the daytime and a not so noticeably low-concentration region only appeared at the canopy surface. This indicates that the air between the forest and the atmosphere was well mixed vertically in the daytime. The CO₂ concentration increased again after sunset, which was especially marked above the ground layer, indicating that soil respiration dominated the forest carbon exchange during the nighttime.

4 Conclusions

The studies on turbulent exchange of CO₂ over the Changbai Mountain forest suggests that with near-neutral atmospheric stratification, CO₂ and vertical wind velocity components measured over the canopy followed the expected $-2/3$ power law in the inertial sub-range. The dominant vertical eddy scales were about 100 m. The frequency ranges of eddies, contributing to CO₂ fluxes, were mostly within 0.01–2.0 Hz. The large eddies with low frequency over the canopy contributed more to CO₂ fluxes than small eddies. Given that both the Li7500 infrared gas analyzer and the CSAT3 sonic anemometer have a sampling frequency of up to 10 Hz, the eddy covariance system we employed is qualified for eddy flux measurements over forest canopies. However, under neutral and stable atmospheric stratification, the eddy covariance system systematically underestimates the nocturnal CO₂ fluxes. This is because vertical and horizontal advection and even molecular diffusion dominated the CO₂ exchange in the two- and even three-dimensional flowfield when vertical

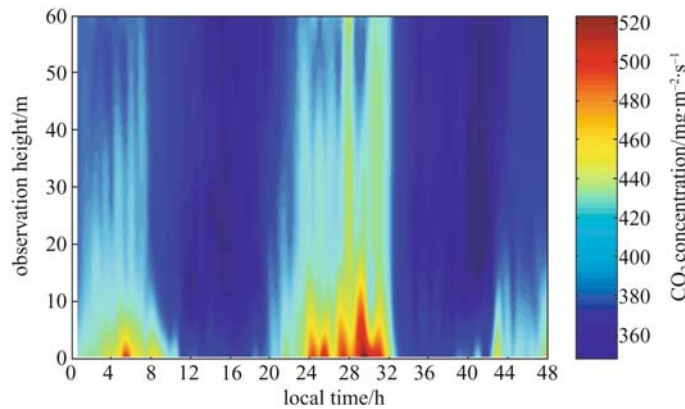


Fig. 6 Spatial-temporal evolution of CO₂ concentration in forest during August 19–20, 2004

turbulent mixing was substantially reduced, while these non-turbulent transfer processes could not be captured by the eddy covariance system. Therefore, we can draw the conclusion that the increase of flux losses through non-turbulence flows is the main limiting factor for the application of the eddy covariance technique and hence the corresponding post-field data quality controls scheme is indispensable under neutral and stable atmospheric conditions. The threshold of friction velocity, which characterizes the turbulence intensity, was 0.2 m/s in the Changbai Mountain forest.

Acknowledgements This study was supported by the National Natural Science Foundation of China (Grant Nos. 40675069 and 30700085).

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