Eddy flux corrections for CO_2 exchange in broad-leaved Korean pine mixed forest of Changbai Mountains

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Abstract Based on analysis of mechanisms causing energy no-closure and nocturnal low fluxes issues for CO_2 exchange studies by eddy covariance method, corrections were done with the raw data sets obtained from Changbai Mountains forest flux site, to evaluate the impacts of sonic anemometer tilt, frequency response limitations and advection on estimation of CO_2 exchange, respectively. The results show that the planar fit coordinate transforming method is superior to the streamline coordinate transforming method in tilt correction. The latter could cause a systematical underestimation of eddy fluxes relating with the angle of sensor and terrain tilt. The underestimation of CO_2 and energy fluxes for frequency response limitations average 3.0% and 2.0% during daytime, respectively, which increase by 9.0% and 5.5% during nighttime, respectively. The corrections of frequency response limitations are closely related to atmospheric stability. The advection loss of CO_2 fluxes is dominated by nocturnal vertical advection, which is at least 18% when the horizontal advection is neglected. It is suggested that more work be done to understand the characteristics of horizontal advection and turbulent eddies under a complex circumstance.

Keywords: eddy covariance method, carbon cycle, flux correction, CO_2 exchange, tilt correction.

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To explore the regional and global carbon cycle and budget, it is important to quantify the CO_2 exchange between the biosphere and atmosphere[1—3]. Eddy covariance (EC) method, which is considered to be the standard tool for measuring mass and energy fluxes to and from terrestrial ecosystems, has been widely applied to observational studies of CO_2 exchange within the FLUXNET community[4]. EC method has a unique contribution to the study of carbon budget and carbon processes in terrestrial ecosystem for it can provide CO_2 transformations information continuously on diurnal, seasonal and annual time scales through direct measurement. However, some puzzling problems also emerged when this method was used under relatively complex environment. One problem with EC method is the lack of energy budget closure, which is particularly serious over forest with high vegetation. The energy fluxes obtained by EC method are always underestimated 10%—30% to that obtained by net radiometer[5]. Because the transformation mechanisms of CO_2 is similar to that of heat and water vapor fluxes in the surface layer, the concern naturally arose about whether the CO_2 fluxes are also underestimated by EC method[6,7]. Another problem is the apparently low EC fluxes at night[8,9]. Recent studies frequently showed that CO_2 fluxes measured by EC method were generally 20%—42% lower compared with the results obtained by chambers method and carbon cycle models[10]. Both ecologists and meteorologists express deep concerns with such problems[11,12], because of their negative impacts on the scientific credibility of carbon budget based on long-term EC method observation. Several workshops for special topic within AmeriFlux and FLUXNET community have been held in response to these concerns, and various points of view have been given[13—15], but as yet no agreement has been reached about the mechanisms that caused the failure of energy budget closure and corresponding underestimations of EC fluxes at night.

Evidences from recent literatures indicated that these phenomena are ascribed to physical limitations of instrument and non-ideal observation environment. Several researchers discussed in further detail and suggested that sonic anemometer tilt, limitations of frequency response and advection loss should be responsible for the underestimations of EC fluxes[8,11,16,17]. Most researchers have accepted these viewpoints[18]. However, the corrections are always neglected intentionally or unintentionally in most flux sites because it is hard to evaluate quantificationally these underestimations. Without some understanding and ability to compensate for these limitations and uncertainties of EC method, cross-site comparisons and global scale synthesis are difficult and questionable. As yet, there is no such a literature that dedicated to discussing the corrections processes and results synthetically based on measured raw data sets. Thus, further studies are still need to explore the correction issues for CO_2 exchange in terrestrial ecosystem based on EC techniques.

In China, the studies of CO_2 exchange by EC method are at the booming stage[19,20]. It is more urgent for us to tackle these problems. This paper firstly analyzes the mechanisms causing energy no-closure and nocturnal low fluxes issues in eddy flux studies, then attempts to evaluate quantificationally the impacts of sonic anemometer tilt, frequency response limitations and advection loss on estimation of CO_2 exchange, based on the raw data sets observed from Changbai Mountains forest flux site.

1 Setting and methods

The experimental site is located within the broad-leaved Koreanpine forest of Changbai Mountains. This site is considered to be an ideal place to carry out studies of mass and energy exchange between forest and atmosphere by micrometeorological methods, for the terrain surrounding the tower is ideally flat and homogeneous.

One set of eddy covariance measurement system was mounted on a 62-m-tall tower. The sensors were placed on a boom located 40 m (one and half tree height) above ground and extending 3 m upwind of the tower, to minimize flow distortion caused by tower structure. Wind velocity fluctuations were measured with three- dimensional sonic anemometer (CSAT3, Campbell Scientific Inc, USA). One fine wire thermocouple (FW05, Campbell Scientific Inc, USA) was attached to sonic anemometer to measure temperature fluctuations. Water vapour fluctuations were measured with a fast response open-path, infrared gas analyzer (Li7500, Li-cor Inc, USA). All sensors responded to frequencies up to 10 Hz. Additionally, one set CO_2 concentration profile system and one set routine meteorological system were also mounted on the tower to make a synchronous auxiliary observation.

The vertical flux densities of mass and energy between vegetation and atmosphere were computed at 30 min intervals with the mean covariance between vertical velocity (w') and the respective scalar (c') fluctuations (e.g. CO_2, water vapor and temperature) according to 'Reynolds' decomposition. All calculations in this paper were done with the package of Matlab 6.5 (MathWorks, Inc, USA).

2 Sonic anemometer tilt correction

Kaimal and Haugen[21] proposed that to measure the vertical wind velocity component accurately, the sonic anemometer should be placed over perfect level terrain with the tilt angle no more than 0.1 degree. Whereas in practice it is hard to level instrument precisely, or the flux site is in a sloping terrain, thus there will always be a deviation from the true mean vertical velocity and a corresponding bias in the flux estimation[22]. To eliminate this bias from eddy fluxes, one has to align the frame of reference with the vertical using a coordinate rotation. It is a common practice for micrometeorologists to place the first coordinate axis along the mean (horizontal) wind direction. To date, the prevailing methods used for tilt correction are streamline coordinate transforming (TR) and planar fit coordinate transforming (PF)[23].

2.1 Streamline coordinate transforming method

In the streamline coordinate transforming system (sometimes called the nature coordinate system), the x-axis is parallel to the local mean horizontal wind ($\bar{u}$) and the z-axis is perpendicular to the x-axis, thus the mean cross-wind ($\bar{v}$) and the mean vertical wind ($\bar{w}$) are zero. The correction process involves a series of rotations, applied at the end of each turbulent averaging period. The first rotation sets $\bar{v}=0$ by rotating the x and y-axes around the z-axis with θ angle:

$$\theta = \tan^{-1}\left(\frac{\bar{v}_m}{\bar{u}_m}\right), \tag{1}$$

so that the new velocity components are given by

$$\begin{aligned} u_1 &= u_m \cos\theta + v_m \sin\theta, \\ v_1 &= -u_m \sin\theta + v_m \cos\theta, \\ w_1 &= w_m, \end{aligned} \tag{2}$$

where subscript m indicates that the mean values are measured values in the tilted frame of reference, and subscript 1 denotes the velocities after the first rotation. The second rotation set $\bar{w}=0$ by rotating the new x and z-axes around y-axis with ϕ angle:

$$\phi = \tan^{-1}\left(\frac{\bar{w}_1}{\bar{u}_1}\right), \tag{3}$$

so that the x-axis points in the mean streamline direction. The final velocity components are then given by

$$\begin{aligned} u_2 &= u_1 \cos\phi + w_1 \sin\phi, \\ v_2 &= v_1, \\ w_2 &= -u_1 \sin\phi + w_1 \cos\phi. \end{aligned} \tag{4}$$

The third rotation sets $\overline{v'w'}=0$ by rotating the y and z-axes around x-axis with ψ angle:

$$\psi = \tan^{-1}\left(\frac{2\overline{v_2 w_2}}{\overline{v_2^{\,2}} - \overline{w_2^{\,2}}}\right), \tag{5}$$

the third set of rotation equations then becomes

$$\begin{aligned} u_3 &= u_2, \\ v_3 &= v_2 \cos\psi + w_2 \sin\psi, \\ w_3 &= -v_2 \sin\psi + w_2 \cos\psi, \end{aligned} \tag{6}$$

then the measured three components of wind velocities u_m, v_m and w_m are transformed to u_3, v_3 and w_3 in the streamline coordinate system.

2.2 Planar fit coordinate transforming method

Wilczak et al.[23] have discussed the PF method in detail. A planar least squares fit is applied to the collection of run mean horizontal and vertical velocities to find constants b_0, b_1 and b_2 in

$$\bar{w}_m = b_0 + b_1 u_m + b_2 v_m, \tag{7}$$

the solution of the least squares problem is given by the following matrix equation:

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 1 & \widetilde{\bar{u}_m} & \widetilde{\bar{v}_m} \\ \widetilde{\bar{u}_m} & \widetilde{\bar{u}_m^2} & \widetilde{\bar{u}_m \bar{v}_m} \\ \widetilde{\bar{v}_m} & \widetilde{\bar{u}_m \bar{v}_m} & \widetilde{\bar{v}_m^2} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \widetilde{\bar{w}_m} \\ \widetilde{\bar{u}_m \bar{w}_m} \\ \widetilde{\bar{v}_m \bar{w}_m} \end{pmatrix}, \tag{8}$$

where a tilde denotes mean values over the collection of run-mean values. The coordinate transforming matrix P (P is a partial rotation matrix that places the z-axis perpendicular to the plane of the mean streamlines) is defined as

$$P = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix}^{-1} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{pmatrix}^{-1}, \tag{9}$$

where

$$\alpha = \arctan(-b_1), \quad \beta = \arctan(b_2), \tag{10}$$

the mean wind velocity components then can be written as

$$\begin{pmatrix} \bar{u}_p \\ \bar{v}_p \\ \bar{w}_p \end{pmatrix} = P \cdot \begin{pmatrix} \bar{u}_m \\ \bar{v}_m \\ \bar{w}_m \end{pmatrix}, \tag{11}$$

rotate the *x*-*y* plane around *z*-axis according to the first coordinate of TR method, and then the velocity components of all runs are in the new frame of reference.

Figure 1 shows the comparison of magnitude between corrected and measured CO_2 fluxes. The former is generally lower than the latter, both for PF and TR methods. It indicates that the false information caused by sonic anemometer and terrain tilt is eliminated with tilt correction, which is crucial to understanding of dynamics and mechanism about forest carbon cycle. The average corrected fluxes in the planar fit coordinate system are 5% higher (in magnitude) than in the streamline coordinate system. In six experimental days, the average CO_2 flux calculated from raw data is −15.52 $gC \cdot m^{-2} \cdot d^{-1}$; the corrected flux based on PF method is −14.95 $gC \cdot m^{-2} \cdot d^{-1}$, and decreases by 3.7%; the corrected fluxes based on TR method is −14.79 $gC \cdot m^{-2} \cdot d^{-1}$, and decreases by 4.7%.

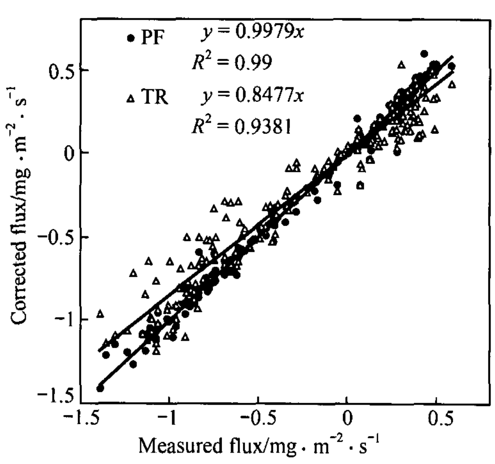

Fig. 1. Impacts of tilt correction on measured CO_2 flux during August 13—18, 2003 at Changbai Mountains forest site.

3 Correction for frequency response limitations

Almost all eddy covariance systems have physical limitations, including the limited time response of the infrared gas analyzer, line averaging, sensor separation and discretized sampling, etc. All these limitations could cause systematic underestimations of eddy fluxes[24,25]. For example, the smallest structure size in atmospheric turbulent eddies is smaller than a millimeter and with high wind speeds (larger than 0.5 $m \cdot s^{-1}$), which means that to capture the transferring information of these turbulence eddies, the frequency of instruments response must at least up to 500 Hz. While the responses of most eddy covariance systems are often much slower than this level. The consequence of such limitations is an underestimation of eddy fluxes, especially during the night, when is characterized as low wind velocities.

With the assumption of spectral similarity between temperature, H_2O and CO_2, and application of a series of transfer functions defined for each correction term, Moore[25] suggested a spectral corrections method to compensate this limitation caused underestimation. Though Horst[26,27] reported a simpler analytical alternative to Moor's comprehensive numerical approach, his development focuses on the slower responding scalar sensors, it does not include the effects of line averaging and sensor separation. Hence the relatively physically sound spectra correction schemes following Moore[25] were used here to recover the underestimations caused by sensor line-averaging, spatial separation and high frequency losses.

The underestimated fluxes caused by frequency response of EC system can be written as

$$\frac{\Delta Fs}{Fs} = 1 - \frac{\int_0^\infty T_{ws}(n) Co_{ws}(n)\,\mathrm{d}n}{\int_0^\infty Co_{ws}(n)\,\mathrm{d}n}, \tag{12}$$

where ΔFs is the underestimated flux, Fs is the true eddy flux, $Co_{ws}(n)$ is the co-spectrum of the scalar flux Fs, and n is natural frequency. During stable conditions, i.e. $(z_m - d)/L > 0$ and $L < 1000$ (here L denotes the Obukhov length), $Co_{ws}(n)$ is written as

$$nCo_{ws}(n)=\frac{f}{A_{ws}+B_{ws}f^{2.1}}, \quad (13)$$

where the quantities A_{ws} and B_{ws} are written as

$$A_{ws}=0.284\left[1+6.4\left(\frac{z-d}{L}\right)\right]^{0.75}, \quad (14)$$

$$B_{ws}=2.34A_{ws}^{-1.1}. \quad (15)$$

The model spectra definitions are based on the normalized frequency $f = n(z_m-d)/u$, where z_m is the measuring height (40 m), d is the zero plane displacement (here use the value of 19.5 m estimated by Liu et al.[28]), and u is the average horizontal wind speed. During unstable conditions the model spectrum is written as

$$nCo_{ws}(n)=\frac{12.92f}{(1+26.7f)^{1.375}} \quad f<0.54, \quad (16)$$

$$nCo_{ws}(n)=\frac{4.378f}{(1+3.8f)^{2.4}} \quad f\geqslant 0.54, \quad (17)$$

$T_{ws}(n)$ is the convolution of all transfer functions associated with frequency response of sensors in question.

$$T_{ws}(n)=G(n)T_a(n)T_{ss}(f_{ss})\sqrt{T_s(f_{p_1})T_w(f_{p_2})}. \quad (18)$$

The transfer functions of each correction term are defined as the following form:

(1) Limited frequency response of the infrared gas analyzer $G(n)$

$$G(n)=\frac{1}{\sqrt{1+(2\pi n\tau)^2}}, \quad (19)$$

where τ is the time constant of sensor response (τ= 0.1 s in here).

(2) Line averaging

If a sensor measures the turbulent flow field over a finite sampling path, the signal of turbulent eddies with size comparable with the sensor path is averaged. In order to take it into account transfer functions should be applied. This function has a different form for scalar and vector quantities. The transfer function for scalar sensor is $T_s(f_{p_1})$:

$$T_s(f_{p_1})=\frac{1}{2\pi f_{p_1}}\left(3+e^{-2\pi f_{p_1}}-4\frac{1-e^{-2\pi f_{p_1}}}{2\pi f_{p_1}}\right), \quad (20)$$

where $f_{p_1}=n\cdot p_1\cdot u^{-1}$ is the normalized frequency. The averaging path is given by p_1. In this system, the Li7500 infrared gas analyzer has an optical path with a length of 0.125 m.

A different transfer function is applied to the sonic anemometer (vector sensor), which has a transducer head-to-head averaging path. The transfer function is defined as $T_w(f_{p2})$:

$$T_w(f_{p_2})=\frac{2}{\pi f_{p_2}}\left(1+\frac{e^{(-2\pi f_{p2})}}{2}-\frac{3(1-e^{(-2\pi f_{p2})})}{4\pi f}\right), \quad (21)$$

where $f_{p_2}=n\cdot p_2\cdot u^{-1}$ is the normalized frequency too, the averaging path of the CSAT3 sonic anemometer is given by p_2 (p_2 = 0.10 m in here). Whereas spatial averaging is relevant for all sensors, the effect on the temperature measured using a thermocouple is considered small enough to ignore a correction for this.

(3) Transfer function for sensor separation is defined as $T_{ss}(f_{ss})$:

$$T_{ss}(f_{ss})=e^{(-9.9f_{ss}^{1.5})}, \quad (22)$$

where $f_{ss}=n\cdot ss\cdot u^{-1}$, and the separation distance between infrared gas analyzer and sonic anemometer is given by ss (ss = 0.25 m in here). Because that the fine wire thermocouple used in this experiment was attached to sonic anemometers, the separation distance between them is so small that correction is ignored here.

(4) Transfer function for discretized sampling is defined as $T_a(n)$:

$$T_a(n) = 1 + \left(\frac{n}{n_s - n} \right)^3, \quad (23)$$

where n_s is the sampling frequency (n_s is 10 Hz for this system).

Figure 2 shows the results of correction for frequency response limitations. During unstable periods, the underestimated fluxes of the EC system positively correlate with wind u. The losses of sensible heat fluxes (H) increase almost linearly with wind u, and those of CO_2/H_2O have the same trends except a bit scatter when the wind u<1 m · s^{-1}, as illustrated in fig. 2(a). To simplify calculation processes, linear equations were fitted to both conditions.

The fitting equation for frequency response limitations of sensible heat fluxes is given by

$$\text{Loss}(\%) = 0.187u - 0.089 \quad (R^2 = 0.9988, n = 13). \quad (24)$$

The fitting equation for frequency response limitations of CO_2/H_2O fluxes under unstable condition is given by

$$\text{Loss}(\%) = 0.143u + 1.398 \quad (R^2 = 0.9901, n = 13). \quad (25)$$

As we can see from fig. 2, the losses of eddy fluxes are much higher during stable conditions than those during unstable conditions. The underestimated fluxes increase with increasing $(z_m-d)/L$ as shown in fig. 2(b), which indicates that when the observational height of z_m keeps constant, low values of the Obukhov length (L) will cause extra losses. For example, when u=3.0 m · s^{-1} and L=10 m, the underestimated flux of CO_2/H_2O is less than 4.0%. In the case of L=10 m, the underestimated flux is more than 15%. Moreover, the underestimations increase with increasing wind velocities, but the response is insensitive. For example, as $(z_m-d)/L$ = 1, the underestimated flux of CO_2/H_2O increases no more than 0.5% when u increased from 0.5 to 5 m · s^{-1}. The underestimation of sensible heat fluxes is apparently lower than that of CO_2/H_2O fluxes, though they have similar variation courses. The difference is ascribed to the fact that the observational system of sensible heat flux has no limitation of sensor separation. The fitting equation for sensible heat fluxes under stable conditions is written as

$$\text{Loss}(\%) = -0.091x^2 + 1.945x + 0.692 \quad (R^2 = 0.9991, n = 21), \quad (26)$$

where $x = (z_m-d)/L$.

The fitting equation for CO_2/H_2O fluxes under stable conditions is written as

$$\text{Loss}(\%) = -0.472x^2 + 7.571x + 3.742 \quad (R^2 = 0.9971, n = 21). \quad (27)$$

It can be seen from fig. 2 that the fitting equation can well describe the relationship between underesti-

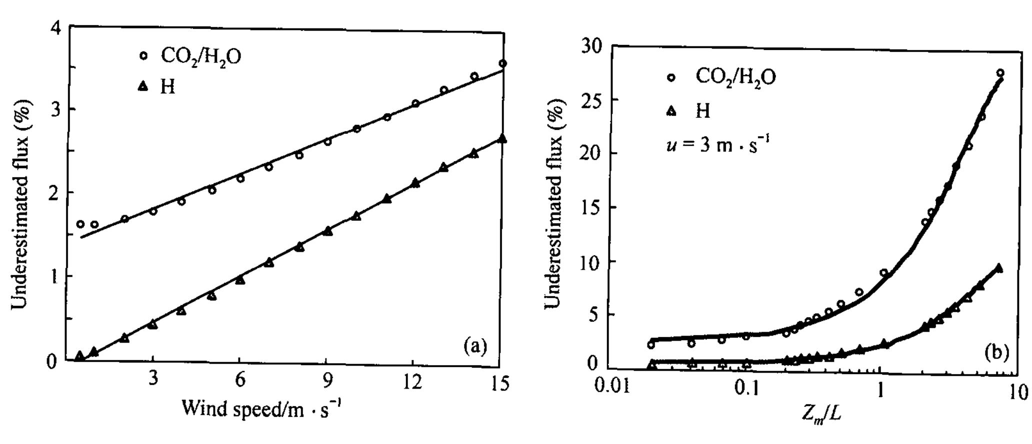

Fig. 2. Frequency response corrections of CO_2/H_2O and sensible heat fluxes during unstable atmospheric stratification (a) and stable atmospheric stratification (b).

mated eddy fluxes and environment parameters. Eq. (25) is quite similar to what was obtained by Goulden[29] from a spruce forest site except that the underestimation of the latter is more serious. The difference between them is probably due to the application of different EC instrument systems.

44% of the cases for the atmospheric stratification are unstable, the average losses of frequency response limitations are about 2.5% for CO_2/H_2O and 1.3% for sensible heat fluxes. 54% of the cases for the atmospheric stratification are stable, and the average losses are about 9.6% for CO_2/H_2O and 2.0% for sensible heat fluxes. The maximum of underestimated fluxes for CO_2/H_2O is more than 20%, but these data runs account for no more than 1% of all data sets. Generally (more than 90%), the values of $(z_m-d)/L$ range from 0.1—2.0, which means that the underestimations are within 3%—15%. The underestimated fluxes under neutral atmosphere conditions (about 2% of total data runs) were estimated using eqs. (24) and (25). The underestimations are 2.3% for CO_2/H_2O and 0.8% for sensible heat fluxes, respectively.

The underestimations of CO_2 and energy fluxes (sensible heat and water vapor fluxes) for frequency response limitations are 3.0% and 2.0% during daytime, respectively, which increase by 9.0% and 5.5% during nighttime, respectively. The difference between them is mostly ascribed to the atmospheric stability in a day.

4 Correction of advection

In theory, the site selected for studies of CO_2 exchange should have an ideally flat terrain, large fetch and uniform source area[30]. While in practice, it is hard to find such a site in field, thus advection is a common feature in studies of mass and energy exchange with the micrometeorological methods. Vertical advection of mass and energy will occur in circumstances when there is flow divergence/convergence, and the non-zero mean vertical velocity can be used to account for this flux losses. Horizontal advection will occur when the underlying surface is heterogeneous[11]. The most prominent situation involves flow across the border of surfaces with different roughness or different source/sink strengths. The horizontal advection is difficult to measure from a single tower, thus no such a study has been done as yet.

The terrain surrounding the Changbai Mountains forest site is ideally flat with uniform vegetation covering. The mixed forest stand extends several kilometers in all directions with the shortest fetch being 400 m. On account of the homogeneous distributions of the scalar source strength within the fetch area, the site is considered to be an ideal place to carry out studies of vertical advection term Fc_{vert}.

$$Fc_{\text{vert}} = \overline{w}\left(\overline{c}_{\text{m}} - \frac{1}{z_{\text{m}}}\int_0^{z_{\text{m}}} \overline{c}\,\text{d}z\right), \tag{28}$$

where $\overline{w}$ and $\overline{c}_{\text{m}}$ are the non-zero mean vertical velocity and scalar concentration at the height of flux observation (z_m); $\overline{c}$ is the mean concentration of CO_2 between floor and observation height.

It is not appropriate to use the mean vertical wind speed measured by the sonic anemometer because of the low signal level, the possible sensor tilt and the aerodynamic shadow of the sensor or the tower. Lee[8] proposed that the true mean vertical velocity $\overline{w}$ can be approximately estimated from the following equation:

$$\overline{w} = \overline{w}_{\text{m}} - a(\phi) - b(\phi)\overline{u}_{\text{m}}, \tag{29}$$

where u_m and w_m are the measured mean horizontal and vertical velocities in the coordinate system defined by the instrument, respectively, $\overline{w}$ is the true mean vertical velocity, and a and b are the wind direction (ϕ) dependent coefficients. Values of a and b are determined by the least squares method as functions of ϕ in 3° intervals using data observed during growing season in 2003. Once the coefficients are determined, eq. (29) is used to calculate $\overline{w}$ for each data run.

During daytime, the vertical advection is quite small in magnitude when compared with intensive transfers of eddy fluxes (fig. 3). This contrasted dramatically with nighttime, during which the Fc_{vert} accounts for nearly 18% of CO_2 eddy fluxes. The maximum loss of vertical advection is 0.3 $\text{mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

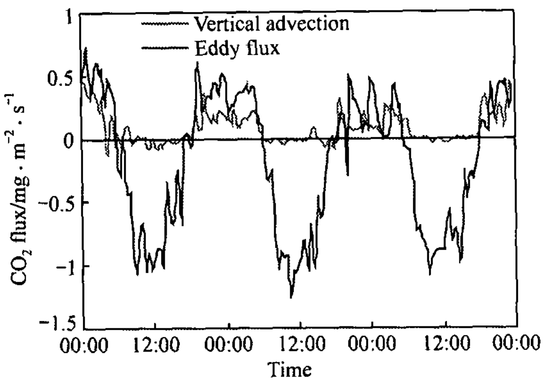

Fig. 3. Variations of vertical advection and CO_2 eddy fluxes during August 9—11, 2003.

Sometimes the magnitude of the underestimation even exceeds that of the CO_2 flux itself. This is due to the high concentration profile between observational height and ground during night. Fig. 4 shows the relationship between the losses of vertical advection and friction velocity. It can be seen that the vertical advection often appears at the stable atmospheric stratification, which indicates that correction of vertical advection is significant to recover the underestimations of nocturnal CO_2 fluxes.

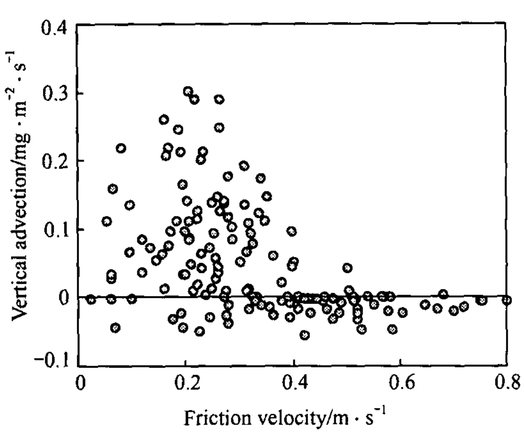

Fig. 4. Scatter plot showing the influence of the friction velocity on the vertical advection.

5 Conclusions and discussions

The correction method of streamline coordinate transforming can be used in real time for each flux-averaging period. While the planar fit coordinate system is defined over a long period (weeks to months) and historical data sets should be reprocessed to estimate fluxes in the new coordinate system, thus this method cannot be used for on-line real-time flux calculations. That's the reason why flux sites prefer TR method to PF method when making tilt correction. However, most of the FLUXNET sites are on undulating or sloping terrain with non-zero vertical velocity. The $\bar{w}=0$ rotation actually acts as a nonlinear high pass filter, which removes the low frequency portion of the fluxes that correspond to periods longer than the averaging period (30 min)[31]. Recent studies have found that the streamline coordinate system is a major contributor to the lack of surface energy balance closure and nocturnal low CO_2 fluxes at many tall forest sites[32]. The PF method is more suitable for tilt correction at forest sites, where are characterized by large-scale turbulent eddies and low frequency component, because it can keep the information of mean vertical velocity. Massman[17] found that eddy fluxes corrected with the planar fit coordinate system are generally 5%—10% higher (in magnitude) than that in the streamline coordinate system. Berger[33] and Wilson[5] got a similar conclusion at forest sites. In this paper, the underestimation was only about 1% in virtue of the ideal observational condition. Considering that most observational towers are in complex terrain, the planar fit coordinate system is the preferred coordinate system for sonic anemometer tilt correction.

The underestimations of CO_2 and energy fluxes for frequency response limitations are 3.0% and 2.0% during daytime, respectively, which increase by 9.0% and 5.5% during nighttime, respectively. Though the correction is based on the physical limitations of instruments system, the results are closely related to atmospheric stability in forest.

Eugster and Siegrist[34] attributed the difference between the fluxes estimated by boundary layer accumulation of CO_2 and the surface eddy fluxes to horizontal advection, they found that the advection was an order of magnitude larger than the local vertical eddy fluxes. Yi et al.[35] inferred the horizontal advection of CO_2 by calculating the vertical flux divergence between different levels on a 447-m-tall tower, and found that advection accounts for 27% of diurnally integrated CO_2 exchange values between levels of 30 and 122 m. But because the scalar source distributions are irregular in vertical profile, their experiments did not tell the precise values of advection terms between the floor and the observational height of fluxes. Several other scientists[11,36,37] have attempted to measure advection, but the results are not very satisfying, considering that the horizontal advection is neglected. Some studies have inferred that the horizontal advection flux indirectly even if the tower sites meet the measurement criteria of flat and horizontal homogeneity. For example, Sun et al.[38] found evidence of the significance of horizontal advection by showing increased concentrations over a lake at night and in the early morning, due to nocturnal advection of respired CO_2 from the surrounding forests by land-breeze circulation. So 18% of CO_2 eddy flux losses caused by vertical advection by this paper possibly underestimated the advection term. Accordingly, how to evaluate the horizontal advection term is still a big challenge for both meteorologists and ecologists.

Nowadays, a common practice to tackle the nocturnal CO_2 fluxes issues is to replace the fluxes during periods with low friction velocity (u^*) by the fluxes estimated with a temperature function (Q_{10}) established using data obtained during well-mixed, high u^* periods[39]. This method may raise some new uncertainty because it assumes the CO_2 source strength is dependent on single environment parameter, while in fact it is modulated by complicated biophysical processes. Furthermore, there is no guarantee that empirical corrections developed at one site will be valid at another. Ideally, one should treat this problem on a physical basis rather than with an empirical correction. Lee's method that evaluates the vertical advection based on mean vertical velocity is a good attempt. To produce defensible conclusions of carbon budget on the regional and global scales for the research community, we must develop a more sound physically-based theory that describes the characteristics of advection and turbulent eddies under complex circumstance.

Synthesizing the correction results of sonic anemometer tilt, frequency response limitations and advection, the nocturnal CO_2 fluxes averagely increased by about 28%, the energy budget closure averagely increased by about 6%. The corrections improve the final results remarkably.

The results of fluxes corrections will be site-dependent, considering the significant differences of observational environment and instrument system among FLUXNET sites. For example, the corrections made by Goulden[29] to a closed-path EC system at NSA-OBS site suggested that just the tube damping of CO_2 fluctuations could cause a nocturnal underestimation as high as 15%—30%. Therefore, some of the conclusions in this paper are not valid at other sites. It is strongly recommended that FLUXNET participants report the correction processes and results at each site, especially at the forest sites with tall vegetation, which will help improve the understanding of the eddy covariance technique through cross-site comparisons.

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References

1. Zhang, R. H., Sun, X. M., Zhu, Z. L. et al., A remote sensing model of CO_2 flux for wheat and studying of regional distribution, Science in China, Ser. D, 1999, 42(3): 325—336.
2. Yu, G. R., Niu D., Wang Q. F., Focal issues in the negotiation of United Nations framework convention on climate change, Resource Science (in Chinese), 2001, 23(6): 10—16.
3. Huang, Y., Study on carbon budget in terrestrial and marginal sea ecosystems of China, Bulletin of the Chinese Academy of Sciences (in Chinese), 2002, 17(2): 104—107.
4. Baldocchi, D., Falge, E., Gu, L. H. et al., FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, B. Am. Meteorol. Soc., 2001, 82(11): 2415—2434.
5. Wilson, K., Goldstein, A., Falge, E. et al., Energy balance closure at FLUXNET sites, Agric. For. Meteorol., 2002, 113: 223—243.
6. Mahrt, L., Flux sampling errors for aircraft and towers, J. Atmos. Ocean. Tech., 1998,15:416—429.
7. Verma, A. B., Baldocchi, D. D., Anderson, D. E. et al., Eddy fluxes of CO_2, water vapor, and sensible heat over a deciduous forest, Boundary-Layer Meteorol., 1996, 36: 71—91.
8. Lee, X. H., On micrometeorological observations of surface-air exchange over tall vegetation, Agric. For. Meteorol., 1998, 91: 39—49.
9. Goulden, M. L., Munger, J. W., Fan, S. M. et al., Measurement of carbon sequestration by long-term eddy covariance: method and a

critical evaluation of accuracy, Global Change Biol., 1996, 2: 169—182.

10. Lavigne, M. B., Ryan, M. G., Anderson, D. E. et al., Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites, J. Geophys. Res., 1997, 102(D): 28977—28985.
11. Baldocchi, D., Finnigan, J., Wilson, K. et al., On measuring net ecosystem carbon exchange over tall vegetation on complex terrain, Boundary-Layer Meteorol., 2000, 96: 257—291.
12. Paw, U. K. T., Baldocchi, D., Meyers, T. P. et al., Correction of eddy-covariance measurements incorporating both advective effects and density fluxes, Boundary-Layer Meteorol., 2000, 97: 487—511.
13. Garratt, J.R., Limitations of the eddy correlation technique for determination of turbulent fluxes near the surface, Boundary-Layer Meteorol., 1975, 8: 255—259.
14. Moncrieff, J. B., Massheder, J. M., Elbers, J., A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide, J. Hydrol., 1997, 188: 589—611.
15. Running, S. W., Baldocchi, D. D., Turner, D. P. et al., A global terrestrial monitoring network inte-grating tower fluxes, flask sampling, ecosystem modeling and EOS satellite data, Remote Sens. Environ., 1999, 70: 108—127.
16. Vickers, D., Mahrt, L., Quality control and flux sampling problems for tower and aircraft data, J. Atmos. Ocean. Tech., 1997, 14: 512—526.
17. Baldocchi, D., Hicks, B. B., Meyers, T. P., Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods, Ecology, 1988, 69: 1331—1340.
18. Massman, W. J., Lee, X. H., Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges, Agric. For. Meteorol., 2002, 113: 121—144.
19. Mao, Z. J., Summary of estimation methods and research advances of the carbon balance of forest ecosystems, Acta phytoecologica Sinica (in Chinese), 2002, 26(6): 731—738.
20. Wu J. B, Zhang, Y. S., Guan, D. X., Methods and progress of studying on CO_2 flux of forest ecosystem, J. Northeast For. U. (in Chinese), 2002, 31(6): 49—51.
21. Kaimal, J. C., Haugen, D. A., Some errors in the measurement of Reynolds stress, J. Appl. Meteorol., 1969, 8: 460—462.
22. Gash, J. H. C., Dolman, A. J., Sonic anemometer (co)sine response and flux measurement I. The potential for (co)sine error to affect sonic anemometer-based flux measurements, Agric. For. Meteorol., 2003, 119: 195—207.
23. Wilczak, J. M., Oncley, S. P., Stage, S. A., Sonic anemometer tilt correction algorithms, Boundary-Layer Meteorol., 2001, 99: 127—150.
24. Kaimal, J. C., Clifford, S. F., Lataitis, R. J., Effect of finite sampling on atmospheric spectra, Boundary-Layer Meteorol., 1989, 47: 337—347.
25. Moore, C. J., Frequency response corrections for eddy correlation systems, Boundary-Layer Meteorol., 1986, 37: 17—35.
26. Horst, T. W., A simple formula for attenuation of eddy fluxes measured with first-order response scalar sensors, Boundary-Layer Meteorol., 1997, 82:219—233.
27. Horst, T. W., On frequency response corrections for eddy covariance flux measurements, Boundary-Layer Meteorol., 1999, 94: 517—520.
28. Liu, H. P., Liu, S. H., Zhu, T. Y. et al., Determination of aerodynamic parameters of Changbai Mountains forest, Acta Scientiarum Naturalium of Universitatis Peckinensis (in Chinese), 1997, 33(4): 522—528.
29. Goulden, M. L., Daube, B. C., Fan, S. M. et al., Physiological responses of a black spruce forest to weather, J. Geophys. Res., 1997, 102 (D): 28987—28996.
30. Zhou, J. W., Huang, Y., Zheng, X. H. et al., Static opaque chamber-based technique for determination of net exchange of CO_2 between terrestrial ecosystem and atmosphere, Chinese Science Bulletin, 2004, 49(4): 381—388.
31. Sakai, R. K., Fitzjarrald, D. R., Moore K E. Importance of low-frequency contributions to eddy fluxes observed over rough surfaces, J. Appl. Meteorol., 2001, 40: 2178—2192.
32. Finnigan, J. J., Clement, R., Malhi, Y., A Re-Evaluation of Long-Term Flux Measurement Techniques Part I: Averaging and Coordinate Rotation, Boundary-Layer Meteorol., 2002, 107: 1—48.
33. Berger, B. W., Davis, K. J., Yi, C., Long-term carbon dioxide fluxes from a very tall tower in a northern forest: flux measurement methodology, J. Atmos. Ocean. Tech., 2001, 18(4): 529—542.
34. Eugster, W., Siegrist, F., The influence of nocturnal CO_2 advection on CO_2 flux measurements, Basic App. Ecol., 2000, 1: 177—188.
35. Yi, C., Davis, K. J., Bakwin, P. S. et al., Influence of advection on measurement of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower, J. Geophys. Res., 2000, 105(D): 9991—9999.
36. Aubinet, M., Heinesch, B., Yernaux, M., Horizontal and vertical CO_2 advection in a sloping forest, Boundary-Layer Meteorol., 2003, 108: 397—417.
37. Staebler, R. M., Fitzjarrald, D. R., Observing subcanopy CO_2 advection, Agric. For. Meteorol., 2004, 122: 129—242.
38. Sun, J., Desjardins, R., Mahrt, L. et al., Transport of carbon dioxide, water vapor, and ozone by turbulence and local circulations, J. Geophysi. Res., 1998, 103(D): 25873—25885.
39. Black, T. A., Hartog, G., Neumann, H. H. et al., Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest, Global Change Biol., 1996, 2(3): 219—229.