Correcting method of eddy covariance fluxes over non-flat surfaces and its application in ChinaFLUX

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Abstract Although Eddy Covariance (EC) technique is one of the best methods for estimating the energy and mass exchanges between underlying surface and atmosphere in micrometeorology, errors and uncertainties still exist without necessary corrections. In this paper, we will focus on the effect of coordinate system on the eddy fluxes. Based on the data observed over four sites (one farmland site, one grassland site and two forest sites), the effects of three coordinate system transforming methods (Double Rotation-DR, Triple Rotation-TR and Planar Fit-PF) on the turbulent fluxes are analyzed. It shows that (i) the corrected fluxes are more or less than the uncorrected fluxes, which is related mainly to the sloping degree of surface, wind speed and wind direction; and (ii) pitch angle has a sinusoidal dependence on wind direction, especially in the regular sloping terrain; and (iii) PF method is something like the simplification of TR or DR, and there are not obvious distinctions in correction in sloping grassland and flat farmland, but PF method is not suitable for uneven and irregular forest sites.

Keywords: eddy covariance fluxes, unhomogeneous surfaces, coordinate transform, correction, ChinaFLUX.

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The increase of carbon dioxide concentration in the atmosphere since the mid-nineteenth century is now well documented[1], and it is regarded as one of the main causes of temperature increase. Consequently, the source or sink of CO_2 and the exchange of CO_2 as well as water and heat become one of the global focuses[2—4]. Estimating CO_2 sequestration of forests is particularly important, in connection with the global change studies and the Kyoto protocol[5]. The elucidation of the circulation of carbon, water and other greenhouse gases and their budgets in various land ecosystems is an important task[6].

To estimate more accurately intake and emission CO_2, as well as other energy exchanges, many fluxes observation stations have been established in many western and other Asian countries[7—11]. Recently, eddy covariance methods have been used in China[12,13] and eight fluxes observation sites (4 forest sites, 3 grassland sites and 1 farmland site) have been established in China[14—16]. One or more eddy covariance systems have been installed in all 8 sites. Nowadays, although eddy covariance techniques have allowed long-term continuous flux measurements of scalars such as CO_2 and water vapor to be made on a routine basis[4,6], and it is regarded as the best method for measuring the fluxes between surface and atmosphere, errors and uncertainties still exist.

Kell, W. et al.[17] analyzed the data from FluxNET and partial Euro-FluxNet and concluded that energy imbalance exist widely in nearly all stations. Massman, W. J. et al.[18] analysed the uncertainties of eddy covariance measurements of carbon and energy exchanges and got 6 main error sources, which include the physical limitation of instruments, the influence of 3-D effects such as drainage and advection, underestimation of eddy covariance fluxes due to inability to measure low frequency contributions, coordinate systems choice, nighttime flux measurements, etc. In practice, some errors are random and inescapable, some are known but difficult to correct, and some are avoidable or can be corrected.

In this paper, we will focus on the effect of coordinate system on the fluxes measurements. The purposes of the paper are: (i) to introduce three methods for correcting fluxes measurements resulting from sensors tilt caused inevitably or naturally; (ii) to compare the differences of the corrected fluxes by three methods; and (iii) to analyze the effect of coordinate rotation on the measurements obtained over four sites.

1 Theories and methodology

In general, fluxes measurements are expected to perform over a flat and homogeneous field, except for no suitable site. Sonic anemometer is installed as perpendicular to the horizontal plane as possible. Nevertheless, in many micrometeorological observation sites, it is difficult to satisfy perfectly the conditions mentioned above. Kaimal and Haugen[19] suggested that the anemometer should be leveled to within 0.1 degree and the terrain must be level to a small fraction of a degree. Otherwise, the fluxes must be corrected based on tilt, surface and atmospheric conditions.

To correct the effect of sensors tilt or sloping terrain on fluxes measurements, many coordinate systems can be used. Wilczak, J. M. et al.[20] analyzed and concluded the reasons for the choice of a streamline coordinate: (i) to make the data readily comparable to analytical theories, which are most easily cast in the streamline coordinate system; (ii) to generate parameterizations that minimize the effect of the sloping terrain, and the results are easily compared to that obtained over a flat terrain; and (iii) to produce turbulence parameterizations that are easily implemented in numerical models. Of course, the streamline coordinate system has its disadvantages, for instance, it neglects the influence that the terrain slop maybe alter the sharp of the low-level profile due to the diabatic effects, which generates Pressure Gradient Forces (PGFs).

1.1 Sonic rotation by individual data run

If the tilt angles are known, coordinate system can be transformed easily. This technique, which is most commonly applied to determining the angles to place the sonic anemometer into a streamline coordinate system, involves a series of two or three rotations, is applied at the end of each turbulent averaging period. It means that the rotating angles of each data run are different. Kaimal and Finnigan[21] described the step and method in detail. Here some brief introduction is given. The first rotation will let x-axis point to wind direction and let $\overline{v}=0$. The first-rotated wind velocities (u_1, v_1 and w_1) are given by

$$u_1 = u_m \cos\theta + v_m \sin\theta, \quad (1)$$

$$v_1 = -u_m \sin\theta + v_m \cos\theta, \quad (2)$$

$$w_1 = w_m, \quad (3)$$

where $\theta = \tan^{-1}(v_m/u_m)$, u_m, v_m and w_m are latitudinal, longitudinal and vertical wind speed observed by 3-D sonic anemometer, respectively. The second rotation sets $\overline{w}=0$ by swinging the new x-axis and z-axis and x-axis points to the mean streamline direction. The second-rotated wind velocities (u_2, v_2 and w_2) can be calculated by

$$u_2 = u_1 \cos\varphi + w_1 \sin\varphi, \quad (4)$$

$$v_2 = v_1, \quad (5)$$

$$w_2 = -u_1 \sin\varphi + w_1 \cos\varphi, \quad (6)$$

where $\varphi = \tan^{-1}(w_1/u_1)$; The third rotation sets $\overline{wv}=0$, which was suggested by McMillen. The purpose is to remove the ambiguity of $\overline{wv}$ on the true stress. The third-rotated wind velocities (u_3, v_3 and w_3) can be expressed as

$$u_3 = u_2, \tag{7}$$

$$v_3 = v_2 \cos\psi + w_2 \sin\psi, \tag{8}$$

$$w_3 = -v_2 \sin\psi + w_2 \cos\psi, \tag{9}$$

$$\psi = \tan^{-1}\left[2\overline{v_2 w_2} \Big/ \left(\overline{v_2^2} - \overline{w_2^2}\right)\right]. \tag{10}$$

After Double Rotation (DR) or Triple Rotation (TR), the corrected scalar (s) flux can be calculated by

$$\begin{aligned} F_{\mathrm{DR}} &= \overline{w_2's'} = -\sin\phi\cos\theta\overline{u's'} \\ &\quad + \sin\phi\sin\theta\overline{v's'} + \cos\phi\overline{w's'}, \end{aligned} \tag{11}$$

$$\begin{aligned} F_{\mathrm{DR}} &= \overline{w_3's'} = (\sin\theta\sin\psi - \sin\psi\sin\phi\cos\theta)\overline{u's'} \\ &\quad -(\sin\phi\sin\theta\sin\psi + \cos\theta\sin\psi)\overline{v's'} + \cos\phi\cos\psi\overline{w's'}. \end{aligned} \tag{12}$$

All the mean covariances of eqs. (11) and (12) are the results observed directly by the instruments.

1.2 Planar Fit (PF) method

PF is a restively new method and first presented by Steve Stage[20]. To understand the idea and method, the sketch map of two coordinate systems is given in fig. 1. The ideas and steps of PF method are: (i) to get a plane ($X_1O_1Y_1$ in fig. 1) on which mean vertical velocity can be expressed as the function of mean horizontal wind speed, on the basis of partial observed 3-D wind speed data; (ii) to calculate new vertical velocity (in general, it is close to but not always equal to zero) via some transformation; (iii) to rotate x-axis and let it point to horizontal wind direction; and (iv) to calculate true fluxes using the covariances of scalars with 3-D velocities. In other words, PF coordinate is a right-handed orthogonal coordinate in which the z-axis is perpendicular to the plane of the mean streamline and the x-axis is parallel to the mean wind direction for each observation. Now, main process of PF method will be given.

If the positions of instrumental sensors are not altered for a period, the instrument-measured vertical wind speed w is related to the horizontal wind speed (u, v). It can be expressed as

$$\overline{w} = b_0 + b_1\overline{u} + b_2\overline{v}, \tag{13}$$

where b_1,b_1 and b_2 are regression coefficients. Now we give a simple derivation of the coefficients using multiple linear regressions. To find the best-fit plane to the velocity data we wish to minimize the function S, where

$$S = \sum_{i=1}^{n}(\overline{w}_i - b_0 - b_1\overline{u}_i - b_2\overline{v}_i), \tag{14}$$

where $\overline{u}_i$, $\overline{v}_i$ and $\overline{w}_i$ are the mean velocities of 3-D

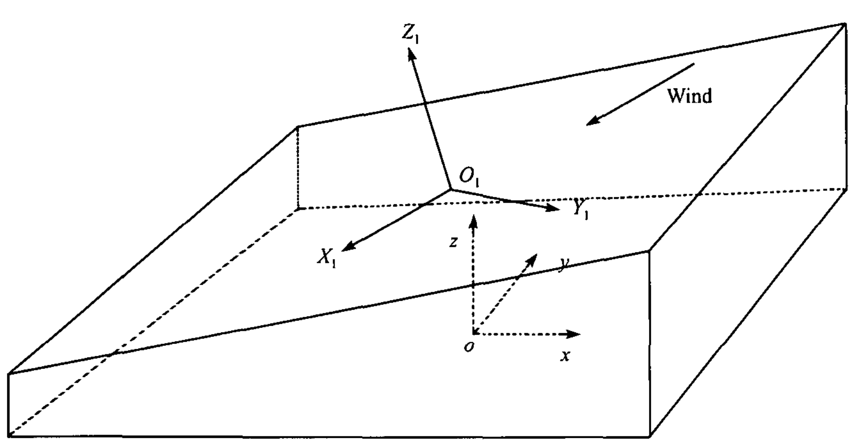

Fig. 1. Sketch of coordinate rotation over sloping terrain. OXY plane is horizontal, and OZ is per pendicular to XOY plane, which denotes the directions of sonic anemometer measurements. Instead, $X_1O_1Y_1$ plane is parallel to sloping surface, and O_1Z_1 is perpendicular to the $X_1O_1Y_1$ plane, vector O_1X_1 points to the mean wind direction during a data run (e.g. 30 min).

for each data run, measured in the sonic anemometer's coordinate system. Differentiating S with respect to b_0, b_1 and b_2 and setting each partial derivative equal to zero resulting in the following three normal equations:

$$\begin{aligned} &nb_0 + (\Sigma\overline{u}_i)b_1 + (\Sigma\overline{v}_i)b_2 = \Sigma\overline{w}_i, \\ &(\Sigma\overline{u}_i)b_0 + (\Sigma\overline{u}_i^2)b_1 + (\Sigma\overline{u}_i\overline{v}_i)b_2 = \Sigma\overline{u}_i\overline{w}_i, \\ &(\Sigma\overline{v}_i)b_0 + (\Sigma\overline{u}_i\overline{v}_i)b_1 + (\Sigma\overline{v}_i^2)b_2 = \Sigma\overline{v}_i\overline{w}_i, \end{aligned} \tag{15}$$

where n is the sampling number. The solutions (b_1, b_1 and b_2) of the three equations provide the linear regression of $\overline{w}_i$ on $\overline{u}_i$ and $\overline{v}_i$. Once b_1, b_1 and b_2 are determined, the PF corrected scalar fluxes can be calculated by the following equation:

$$F_{\mathrm{PF}} = \overline{w_p's'} = p_{31}\overline{u_m's'} + p_{32}\overline{v_m's'} + p_{33}\overline{w_m's'}, \tag{16}$$

where w_p is vertical velocity on the mean streamline plane, P_{31}, P_{32} and P_{33} are the coefficients, which can be calculated by the following equations:

$$\begin{aligned} P_{31} &= -b_1\Big/\sqrt{b_1^2+b_2^2+1}, \\ P_{32} &= -b_2\Big/\sqrt{b_1^2+b_2^2+1}, \\ P_{33} &= 1\Big/\sqrt{b_1^2+b_2^2+1}. \end{aligned} \tag{17}$$

2 Sites and instrumentations

To compare the influence of coordinate transformation, four types of underlying surfaces (sites) were selected. The first site is a sloping terrain (marked as "A"), which is located in the Xilin River Basin (43° 30′N, 117° 27′E, 1189 m.) in Inner-Mongolia Grassland Ecosystem Research Station of Chinese Ecosystem Research Network (IMGERS, CERN), Chinese Academy of Sciences (CAS). The vegetation consists mainly of typical steppe and meadow steppe, such as *Leymus chinense*, *Stipa grandis*, *Stipa Baicalensis*, *Festuca Lenesis*. The sloping degree is about 10—15°. The site is very open and there are not any constructions around. The second site ("B") is relatively flat farm field, which located in Yucheng Integrated Agricultural Experimental Station of CERN, CAS (36° 57′N, 116° 36′E, 28 m). The surface was covered with wheat from March to May (studying periods). The third site ("C") is located in Changbai Mountains Research Station of Forest Ecosystem of CERN, CAS (42° 24′9″N, 128° 05′45″E, 761 m). It is broad-leaved mixed forest and the preponderant species are *Pinus koraiensis, Tilia amurensis*, *Acer mono*, etc. The mean forest height is about 26 m. A 61.8 m high observation tower stands in the site. The topography is relatively flat but the canopy top is still a little rolling, and the EC sensors are installed at 50 m height. The fourth site ("D") is located in the Qianyanzhou Experimental Station of Red Earth Hilly Comprehensive Development of CERN, CAS, (26° 44′N, 115° 04′E, 100 m). The relative height difference is 20—50 m, the topography belongs to mild hill. The station is located on the typical red earth hilly region in the mid-subtropical monsoon landscape zone of South China. The vegetation is man-planted forest. The dominant species are *Pinus elliottii, Pinus massoniana*, etc. Because of the high closure of canopy, the vegetation under canopy is poorly developed and distributed sporadically.

The main instruments of four sites are the same. They include a Open-Path Eddy Covariance (OPEC), with a 3-D sonic anemometer/thermometer (CSAT3, Campbell Sci. Co., USA) and a H_2O/CO_2 analyzer (Li-7500, Li-COR Co., USA). In addition, some supporting observations were executed. It consists of air temperature and humidity (HMP45C, VAISALA Co., Finland), wind speed (A100R, Vector Instrument, UK), soil temperatures (TCAV, 105T and 107, Campbell Co., USA) and moist (TDR, CS615_L, Campbell Co., USA). Net radiation was measured with 4-components method (CM11, KIPP&ZONEN, the Netherlands), and two soil flux plates (HFP01SC, Hukseflux Thermal Sensors, the Netherlands) were buried under 3 cm depth. The data logger is CR5000 (Campbell Sci. Co., USA), sampling rate is 10 Hz, averaging time is 30 min, CO_2 and water Fluxes were corrected by using WPL conversion[22].

3 Results and discussions

3.1 The effect of coordinate system transformation on the fluxes over different surfaces

Up to date, TR method is widely applied for research[20]. In the study, all the results will be compared with the TR corrected results. Fig. 2 shows the comparisons of the sum of sensible and latent heat fluxes (*H+LE*) corrected by TR and No Rotation (NR) over four surfaces. It is clear that the effects of TR method on the fluxes are different in four underlying surfaces. For the sloping grassland (fig. 2(a)), there are large disparities between the TR corrected flux and uncorrected flux, the maximum differences of them can be roughly 80% larger than that of uncorrected fluxes. But for flat cropland surface (fig. 2(b)), the differences of two fluxes are so small that it can be neglected. All data are scattered near 1 : 1 line. As the topography of Changbai Mountains site is more smooth than that of Qianyanzhou site, the scatter of the two fluxes in the former (fig. 2(c)) is less than that of the latter (fig. 2(d)). The TR corrected fluxes may be larger than, equal to or smaller than the uncorrected fluxes. The corrections are mainly decided by the sloping degree of surfaces, wind direction and wind speed.

3.2 The comparisons of relationship between pitch angle and wind direction

In general, the vertical wind speed sensor of sonic anemometer is basically perpendicular to the horizon. However, the horizontal flow may be distorted near the ground, and it will produce a additional vertical vector, and its direction (upward or downward) and magnitude depend on the horizontal wind direction and speed. Fig.3 shows the changes of pitch angles with the wind directions. Over sloping surface, the variation pattern presents a perfectly sinusoidal curve, as shown in fig. 3(a), and the maximum pitch angle is about 8°. Because of the relatively large sloping degree and regular sloping direction, the vertical wind will be affected strongly by the horizontal wind, and different directional wind will induce different vertical vectors. For the flat cropland (fig. 3(b)),

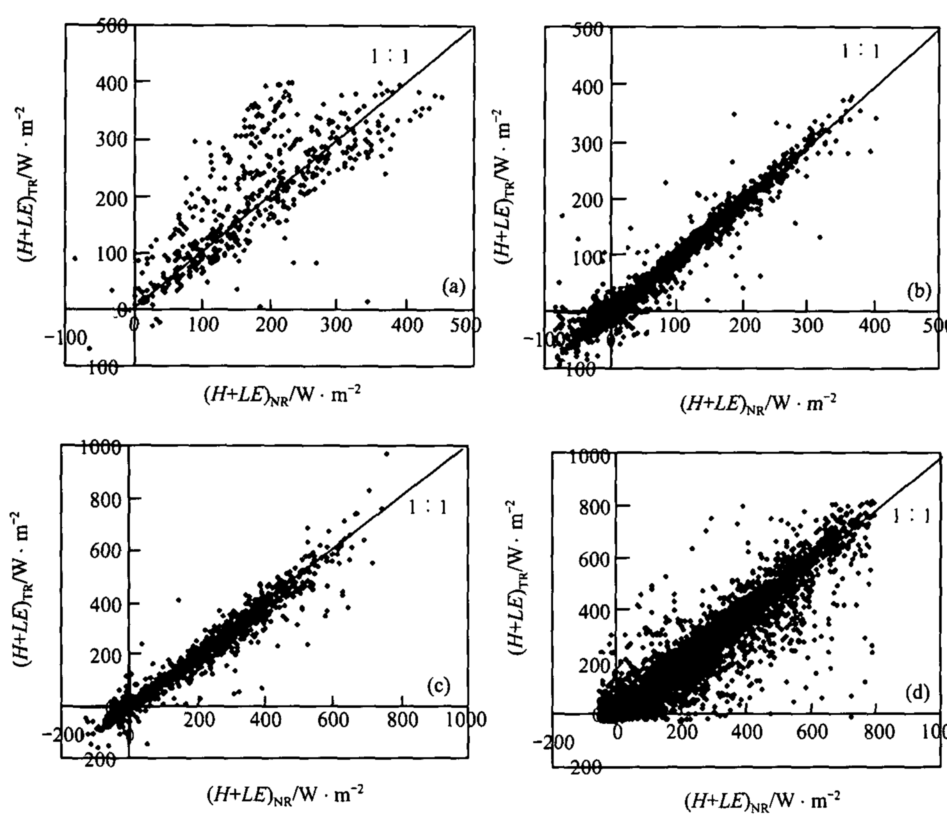

Fig. 2. Comparisons of the sum of sensible and latent heat fluxes (*H+LE*) corrected by TR method and uncorrected (NR) in four sites. (a) Inner-Mongolia grassland; (b) Yucheng farmland; (c) Changbai Mountains forest; (d) Qianyanzhou forest.

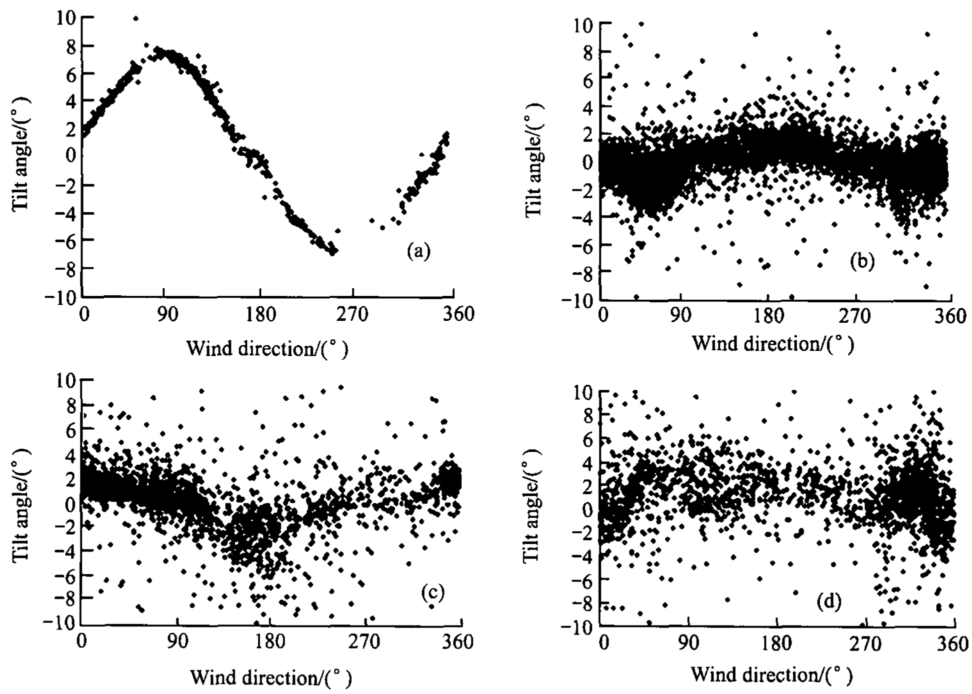

Fig. 3. Comparisons of the relationship between pitch angle and wind direction in four sites. (a) Inner-Mongolia grassland; (b) Yucheng farmland; (c) Changbai Mountains forest; (d) Qianyanzhou forest.

the sinusoidal relationship of two angles is not so obvious, and the maximum angle is about 3°. The relationships of them over two forest sites are not so clear too (fig. 3(c), (d)). The possible reasons are: (i) the changes of topography near tower are irregular and the top canopy is rolling; and (ii) the height of sonic anemometer is so high from top forest canopy that the effect of horizontal flow on the vertical movement is weakened.

3.3 Comparison of vertical velocities before and after PF method correction

As we know, the DR or TR corrected vertical wind speeds are always equal to zero during a data run, e.g. 30 min. However, because the basic idea of PF method is to find an average plane, over which the vertical speeds are smallest, the PF corrected vertical wind speeds are not surely equal but close to zero during a data run. Fig. 4 shows the vertical wind speed before and after PF correction, the corrected *w* is very close to zero. Especially for sloping surface, as shown in fig. 4(a), the uncorrected *w* is very large due to the effect of slope on the flow streamline. However, the effect of PF method on vertical wind speed is not very notable in the Qianyanzhou site, the corrected *w* is still relatively big (fig. 4(b)). It means that it is difficult to find a fitted plane on which the *w* is close to zero. The PF method may not be fitted to the correction in the Qianyanzhou site.

3.4 The comparison of fluxes corrected by three methods

Figure 5 presents the comparison of *Fc* corrected by DR and TR methods. Although DR and TR are the similar methods, distinctions still existed in all sites. Overall, DR corrected *Fc* are smaller than that of TR. Especially in sloping surface, as shown in fig. 5(a), the slope and coefficient of determination (R^2) are clearly smaller than that of other sites. In even farmland, fig. 5(b), there are not any big differences between them, slope and R^2 are very close to 1. In two forest sites, fig. 5(c) and fig. 5(d), the differences of them are moderate, contrasted with grassland and farmland.

Figure 6 presents the comparison of (*H*+*LE*) corrected by TR and PF methods. Contrasted with the results above, the agreement of two fluxes in sloping

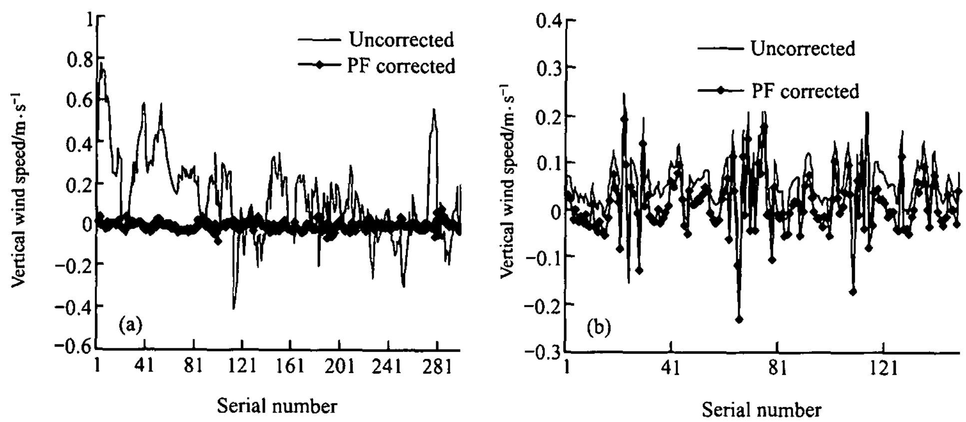

Fig. 4. Comparison of vertical velocity before and after being corrected by PF method in two sites. (a) Inner-Mongolia grassland; (b) Qianyanzhou forest.

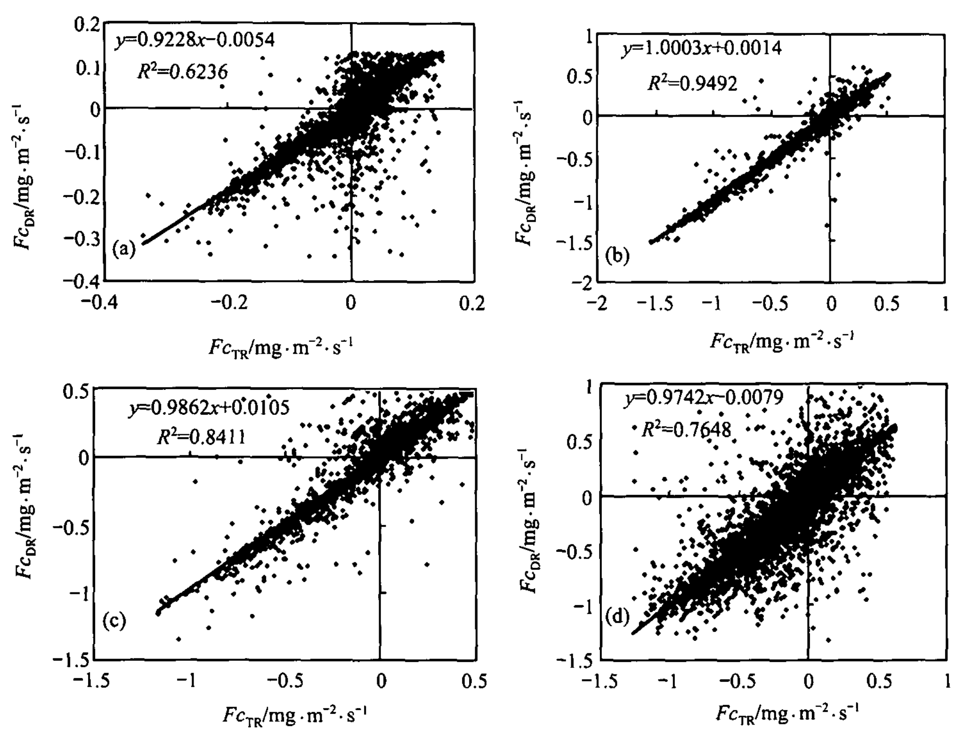

Fig. 5. Comparison of *Fc* corrected by TR and DR methods in four sites. (a) Inner-Mongolia grassland; (b) Yucheng farmland; (c) Changbai Mountains forest; (d) Qianyanzhou forest.

grassland is very good (fig. 6(a)), it means that PF method is suitable for the correction in this site. The similar results can be found in Yucheng site (fig. 6(b)). In Changbai Mountains site (fig. 6(c)), although the slope is close to 1, R^2 is smaller than that in grassland, it implies that there are individual distinctions between two corrections. In the Qianyanzhou site (fig. 6(d)), there are more differences between two corrections. The main cause is that it is difficult to obtain a plane that fits for all directional wind due to the special topography. The PF method may not be appropriate for the correction in the Qianyanzhou site and other complex surfaces.

4 Conclusions

To obtain more exact fluxes using eddy covari-

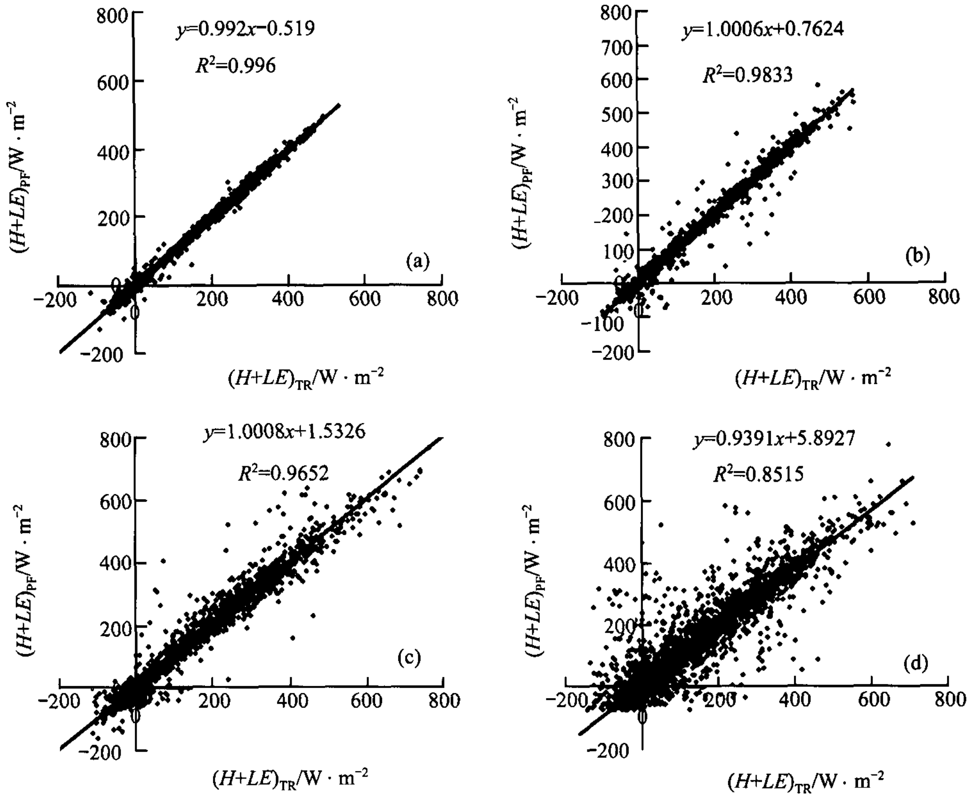

Fig. 6. Comparison of *Fc* corrected by TR and PF methods in four sites. (a) Inner-Mongolia grassland; (b) Yucheng farmland; (c) Changbai Mountains forest; (d) Qianyanzhou forest.

ance technique, coordinate transformation is necessary in most conditions, especially for sloping surface or irregular topography surface. In this paper, we compared the corrected results over four type surfaces using three methods respectively. It shows that (i) the corrected fluxes are more or less than the uncorrected fluxes, which is related mainly to the sloping degree of surface, wind speed and wind direction; (ii) pitch angle has a sinusoidal dependence on wind direction, especially in the regular sloping terrain; and (iii) PF method is something like the simplification of TR, and there is not obvious distinction in correction in sloping grassland and flat farmland, but the PF method is not suitable for uneven and irregular forest sites, especially for the Qianyanzhou station.

In grassland, the fluxes corrected by DR, TR and PF are very close but different from the uncorrected fluxes. However, due to the relatively homogeneous and flat surface in the Yucheng site, whether the correcting method is NR, DR, TR or PF, hardly are there differences between the fluxes. In the Changbai Mountains site, the fluxes corrected by DR, TR and PF methods are different too, but the differences are smaller than that in the Qianyanzhou site, in which big differences exist, and the PF method is not suitable for the fluxes correction. The PF method is suitable for sloping grassland and flat farmland but not for uneven forest sites.

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