Turbulence flux measurement above the overstory of a subtropical *Pinus* plantation over the hilly region in southeastern China

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Abstract Continuous turbulence flux measurement using the eddy covariance (EC) technique was made from January 1 to December 31 in 2003 at two and three canopy heights of a subtropical *Pinus* plantation on the red earth hilly region in southeastern China. To be able to make sure that the measured turbulence flux will equal the net ecosystem/atmosphere exchange, the quality of the data has to be assessed. Three criteria were investigated here, including the power spectra and cospectra analyses, flux variance similarity (integral turbulence test) and energy balance closure. The spectral analyses suggested that above-canopy power spectral slopes for all velocity components and scalars such as CO_2, H_2O and air temperature followed the expected –2/3 power law in the inertial subrange, and their cospectral slopes were close to –4/3 power law in the inertial subrange. The important contribution of large-scale motions to energy and mass transfer above the canopy at higher measurement level was also confirmed by the spectral analyses. The eddy covariance systems have the ability to resolve fluctuations associated with small-scale eddies and did not induce an obvious underestimation of the measured turbulence flux. The Monin-Obukhov similarity functions for the normalized standard deviation of vertical wind speed and air temperature were well-defined functions of atmospheric stability at two heights above the forest canopy, which indicated that turbulence flux measurements made at two heights were within the surface layer. Nocturnal flux underestimation and departures of this normalized standard deviation of vertical wind speed similarity function from that expected from Monin-Obukhov theory were a function of friction velocity. Thus, an optimal criterion of friction velocity was determined to be greater than 0.2—0.3 m s^{-1} for nocturnal fluxes so that the eddy covariance flux measurement was under high turbulent mixing conditions. Energy balance closure reached about 72%—81% at the studied site, which was comparable to the 10%—30% of energy imbalance reported in the literature. However, the energy balance closure could be only used as a useful reference criterion.

Keywords: eddy covariance, power spectra, cospectra, Monin-Obukhov similarity, energy balance closure, nocturnal turbulence flux.

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The elucidation of the circulation of carbon, water and other greenhouse gases and their budgets in various land ecosystems is an important task[1—3]. In recent years the eddy covariance (EC) technique has emerged as an alternative way to assess ecosystem carbon, water and energy exchange[1,4—6]. At present, the EC measurements are most trustworthy when they come from micrometeorologically ideally sites, extensive canopies on flat terrain[7,8]. But as we know, realistic terrestrial ecosystem is composed of various patches with fragment landscape, especially, the distribution of forest ecosystem is mainly located in mountainous area with complex terrain, and the land-surface conditions cannot fully meet the demand by the EC technique[7,9,10]. Currently there are more than 100 research groups within the FLUXNET network that deploy the 1D methodology on a continuous basis to investigate energy, water and carbon fluxes between various types of vegetation and the atmosphere and a large number of sites are on non-flat terrain[3]. In non-ideal or more realistic conditions (tall vegetation, non-flat terrain, patchy canopy, free convection, rain, stable stratification), the flow above the canopy become 2- and 3-dimensional, leading to advection that the conventional tower instruments are unable to capture[8,11], which is the major issue that emerged from the EC measurements within the FLUXNET network[7,9,12]. EC measurements made over non-ideal site have value, too, even though annual estimate of net ecosystem CO_2 and energy exchange may be prone to errors because in reality no ideal sites (horizontally uniform and perfectly flat) exist[6]. Flux measurements from complex sites can provide information for the relationship between carbon and phenology as they can quantify how ecosystem-scale carbon fluxes respond to environmental perturbations and they can quantify the factors causing year-to-year variability in carbon fluxes[13].

At present, relatively few long-term studies of carbon dioxide and water vapour fluxes by the EC technique have been made until now in China, especially over forests on complex terrain[14,15]. Recently, Chinese Terrestrial Ecosystem Flux Research Network (ChinaFLUX) has been established including four forest sites (Changbaishan, Qianyanzhou, Dinghushan and Xishuangbanna), three grassland sites (Haibei, Inner Mongolia and Dangxiong) and one agriculture site (Yucheng) since late August in 2002, which applies the EC technique of microclimatology as a main research method to studying fluxes of CO_2, water and heat between vegetation and the atmosphere. EC measurements over tall vegetation on complex terrain was one of the major issues within the FLUXNET network, so did ChinaFLUX[5,16—18]. To be able to compare the results of flux data of different flux measurements, the quality of the flux data must be assessed and controlled. Motivated in larger part by the need to address this question in ChinaFLUX, we analyzed the turbulence flux measurements using the EC technique at two and three canopy heights of Qianyanzhou subtropical *Pinus* plantation on the red earth hilly region, southeastern China. The objectives of this paper focus on the validity of the measurement investigated by three criteria: spectral analysis, flux variance similarity (integral turbulence test) and energy balance closure and how to assess the nocturnal flux underestimation.

1 Materials and methods

1.1 Site description

The studied site, established in late August in 2002, is in Qianyanzhou Experimental Station of Chinese Ecosystem Research Network (CERN) in southeastern China (26°44′52″N, 115°03′47″E, Elevation: 102 m) as part of ChinaFLUX network. The climate is subtropical monsoon. The mean annual air temperature is 17.9℃, mean annual precipitation is 1485 mm, and mean annual evaporation is 1110 mm. Mean annual frost-free period is 323 d. The plantation was planted in 1985 and the average canopy height is about 11—12 m. The dominant species are *Pinus elliottii*, *Pinus massoniana*, etc. According to the survey in 1999, the mean tree height, diameter at breast height, and density for *Pinus elliottii* were about 10.1 m, 15.6 cm and 1736 stems ha^{-1}, respectively, and those for *Pinus massoniana* were about 8 m, 11.5 cm and 2187 stems ha^{-1}, respectively. The studied site is on gently undulating terrain with slopes among 2.8°—13.5° (for

3-dimensional topography, see http://www.chinaflux.ac.cn/).

1.2 Measurements and instrumentation

Eddy covariance (EC) fluxes were measured at 23.6 m (two canopy height) and 39.6 m (three canopy height) on the main tower. Wind speed and temperature fluctuations were measured with the three-dimensional sonic anemometers (Model CSAT-3, Campbell Scientific) mounted on the tower. CO_2 and water vapour density fluctuations were measured with the open-path CO_2/H_2O analyzers (Model LI-7500, Licor Inc.). All data were recorded at 10 Hz by two CR5000 dataloggers (Model CR5000, Campbell Scientific) and then block-averaged over 30 min for analysis and archiving. The dataset from January 1 to December 31 in 2003 was adopted.

Additional meteorological measurements included radiation measurements made at 41.6 m using a four-component net radiometer (Model CNR-1, Kipp & Zonen), a pyranometer (Model CM11, Kipp & Zonen) and a quantum sensor of photosynthetically active radiation (LI190SB, Licor Inc.). Air temperature and relative humidity sensors (Model HMP45C, Vaisala Inc.) were mounted in ventilated mounts (Model 41002, RM Young Inc.) at seven levels (1.6, 7.6, 11.6, 15.6, 23.6, 31.6 and 39.6 m) above the ground. Soil temperatures were measured at five depths (2, 5, 20, 50 and 100 cm) by thermocouples (105T and 107-L, Campbell Scientific). Soil water contents were measured with three TDR probes (Model CS615-L, Campbell Scientific) at 5, 20 and 50 cm depths. Rainfall was measured by rain gauge (Model 52203, RM Young, Inc.). All data were recorded by three CR10X datalogger (Model CR10XTD, Campbell Scientific) and a CR23X datalogger (Model CR23XTD, Campbell Scientific) with a 25-channel solid-state multiplexer (Model AM25T, Campbell Scientific), respectively.

1.3 Data processing

The EC technique was used to estimate the flux of carbon dioxide, latent heat and sensible heat between forest ecosystem and the atmosphere. Our measurement system produced the above-canopy eddy fluxes of carbon dioxide, latent heat and sensible heat at 30-min intervals and numerically rotated wind velocity axes by triple rotation to compute flux covariance that were aligned normal to the mean streamlines[19]. Correction was made on carbon dioxide and latent heat fluxes for density effects due to heat and water vapour transfer[20]. And affiliated meteorological measurements were also averaged at 30-min intervals for analysis. We limited ourselves to removing spurious values when their cause was clearly identified, which frequently occurred at night. The problems were, in most cases, related to rainfall or water condensation. All computations were done by MATLAB software (Math Works Inc., Natick, MA).

2 Results and discussion

2.1 Spectral analysis of turbulence

With spectra and cospectra it is easy to determine whether the chosen sample rate is high enough. Power spectra ($S_x(f)$) and cospectra ($C_{wx}(f)$) for the vertical velocity (w), CO_2, H_2O and air temperature as measured by the sonic anemometers (T_a) as a function of frequency (f) were calculated using the Welch method. Both the power spectra and cospectra were multiplied by f to force the areas under the curves to correctly represent contributions to the total variance or covariance when plotted semi-logarithmically. $S_x(f)$ and $C_{wx}(f)$ were normalized by the variance of x and the covariance between w and x, respectively.

Power spectra, showing the frequency contributions for w, CO_2, H_2O and T_a are shown in fig. 1. The two salient features from this plot are the spectral peaks and the slopes. In the surface layer where small-scale turbulence is isotropic (independent of rotation and reflection), theory supported by measurements shows an inertial subrange where energy is neither created nor destroyed but rather passed down to progressively smaller scales following a power-law slope of $-2/3$[21,22]. At two measurement heights above the canopy, $S_x(f)$ slopes in the inertial subrange were very close to the expected $-2/3$ for w, CO_2, H_2O and T_a (fig. 1). The results suggested that the instrument effects including the dynamic frequency response of the sonic anemometer and of the IRGA and the scalar path averging did not obviously damp the high-frequency fluctuations. Note that the upward trending value of the spectra at high frequency end is indicative of white noise and aliasing and does not affect the covariances.

In the case of turbulent fluxes of a scalar, the cospectral density, $C_{wx}(f)$ is related to the covariance[21,22]. Cospectral analyses, showing the joint frequency contribution between w and the variable x of the time series to the covariance or flux of variable x, should show a slope of –4/3 on a log-log plot in the inertial subrange. Fig.2 shows that $C_{wx}(f)$ slopes in the inertial subrange were very close to the expected –4/3 for w, CO_2, H_2O and T_a. Although difficult to interpret, fig. 2 also shows that at 23.6 m height (two canopy height), $C_{wx}(f)$ slopes were less than –4/3 through much of the inertial subrange in some degree and more close to −1, similar to the findings of Amiro[23] and Blanken et al.[24].

Plotting $C_{wx}(f)$ against f on a semi-log plot has the advantage of maintaining an area proportional to the covariance between w and x, thus allowing a direct indication of frequency contribution to the flux. There was almost no contribution to the fluxes at frequencies greater than 1 Hz, indicating that sampling frequencies were adequate with no loss of high-frequency fluxes at two measurement heights (fig. 3). The results also suggested that the instrument effects including the sensor response mismatch and sensor separation did not obviously damp the high-frequency fluctuations. The important contribution of large-scale motions to energy and mass transfer above the canopy at higher measurement level was confirmed by the spectral analysis that examines the importance of various frequency contributions to the time series.

2.2 Monin-Obukhov similarity

The Monin-Obukhov (M-O) similarity theory hypothesis states that within the surface layer, various atmospheric parameters and statistics, when normalized by a scaling velocity u_* or temperature T_* become

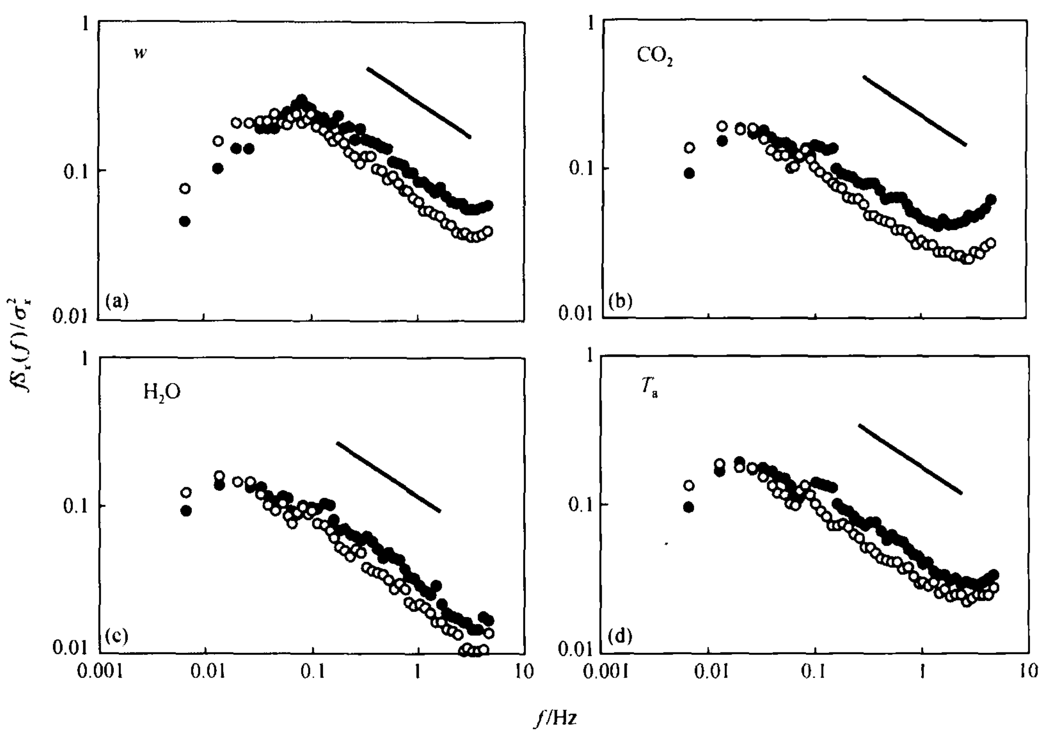

Fig. 1. Mean power spectra $S_x(f)$ for variable x where x is vertical wind velocity component (w), CO_2, H_2O and sonic air temperature (T_a) above the canopy for 8 half-hour period from 1000—1400 CST, October 11, 2003 (z_m=23.6 m for solid spot and z_m=39.6 m for empty spot). Power spectra were multiplied by frequency f and normalized by the variance of x. The solid lines are the −2/3 slope expected in the surface layer inertial subrange. For clarity, means within 40 equally spaced intervals in log f were plotted.

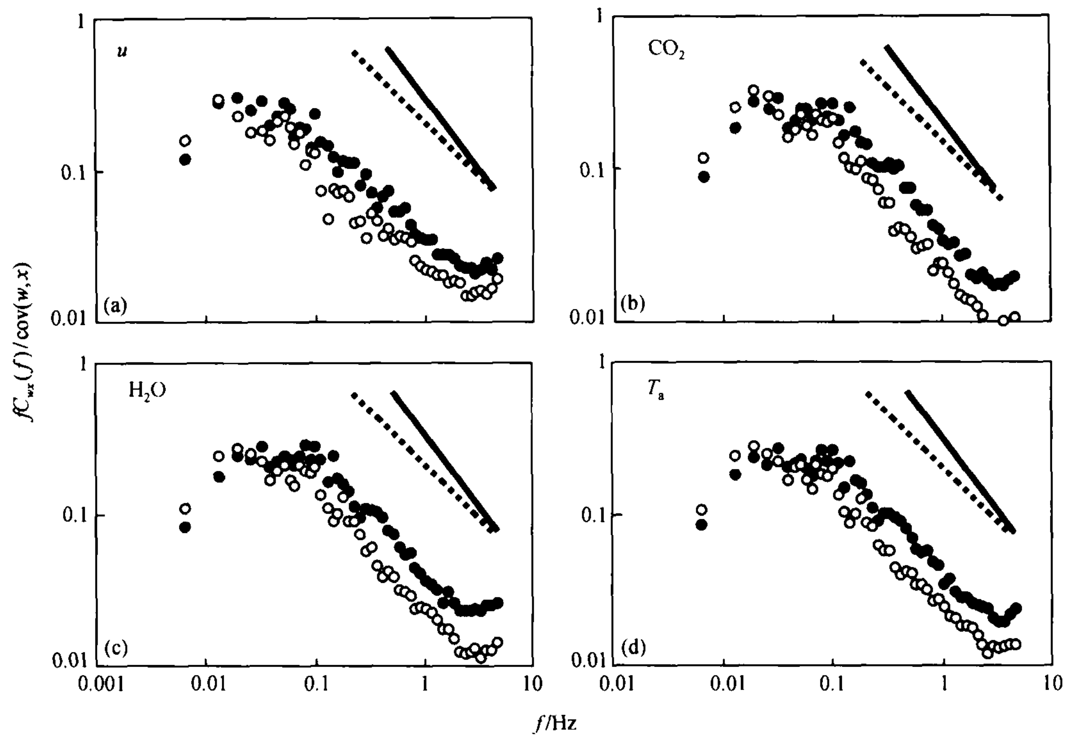

Fig. 2. Mean cospectra $C_{wx}(f)$ between the vertical wind speed (w) and variable where x is horizontal wind speed (u), CO_2, H_2O and sonic air temperature (T_a) above the canopy for 8 half-hour period from 1000—1400 CST, October 11, 2003 (z_m=23.6 m for solid spot and z_m=39.6 m for empty spot). Cospectra were multiplied by frequency f and normalized by the covariance between w and x on log-log plot. Solid line is the –4/3 slope expected in the surface layer inertial subrange and the dash line is the –1 slope. For clarity, means within 40 equally spaced intervals in log f were plotted.

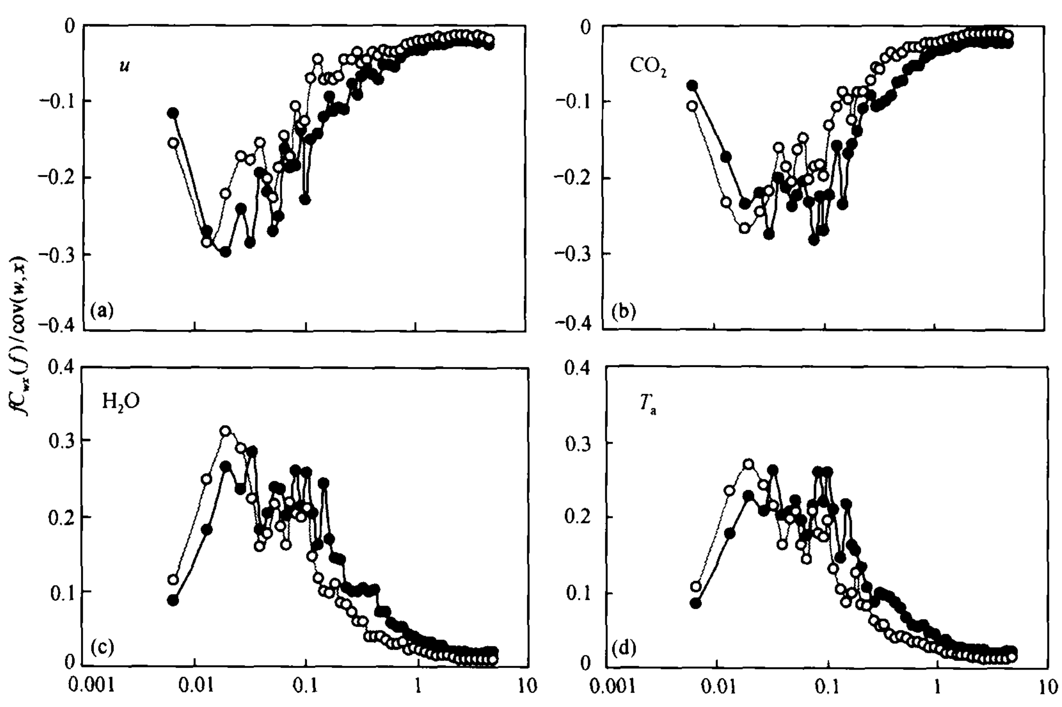

Fig. 3. Same as in fig. 2 except being plotted semi-logarithmically.

universal functions of atmospheric stability, $(z_m-d)/L$, where z_m is the measurement height, d is the zero-plane displacement and L is Monin-Obukhov length. The integral (normalized) turbulence characteristics (flux-variance similarity) may be used as a check on data quality for the EC measurements[5,16,22]. Of particular concern for the EC measurements are the similarity relationships for the vertical velocity and temperature variances. Several empirical fits to these relationships have been found and the common and accepted form of the integral characteristics of the vertical wind for unstable atmospheric stability[22,24] is

$$\frac{\sigma_w}{u_*} = a_1 \cdot \left[1+3\,|(z_m-d)/L|\right]^{b_1}, \qquad (1)$$

and the integral characteristics of the temperature for unstable atmospheric stability[22,24] are

$$\frac{\sigma_T}{|T_*|} = a_2 \cdot \left[1+9.5\,|(z_m-d)/L|\right]^{b_2}, \qquad (2)$$

where a_1, b_1, a_2 and b_2 are empirical coefficients.

By definition, the integral characteristics are basic similarity characteristics of atmospheric turbulence. Therefore, they characterize whether or not the turbulence is well developed according to the similarity theory of turbulent fluctuations. It gives essential information on the site and setup. The data quality is good if the difference between the measured integral characteristics and the calculated value differs by not more than 20%—30%. It is possible to discover some typical effects of non-homogeneous terrain by integral turbulence test[5,25]. Firstly, if there is additional mechanical turbulence caused by obstacles or generated by the measuring device itself, the measured values of integral characteristics of scalars are significantly higher than that predicted by the models. Secondly, the measured values of integral characteristics are significantly higher than that predicted by the models for terrains with an inhomogeneity in the surface temperature and moisture conditions, but not for inhomogeneities in the surface roughness.

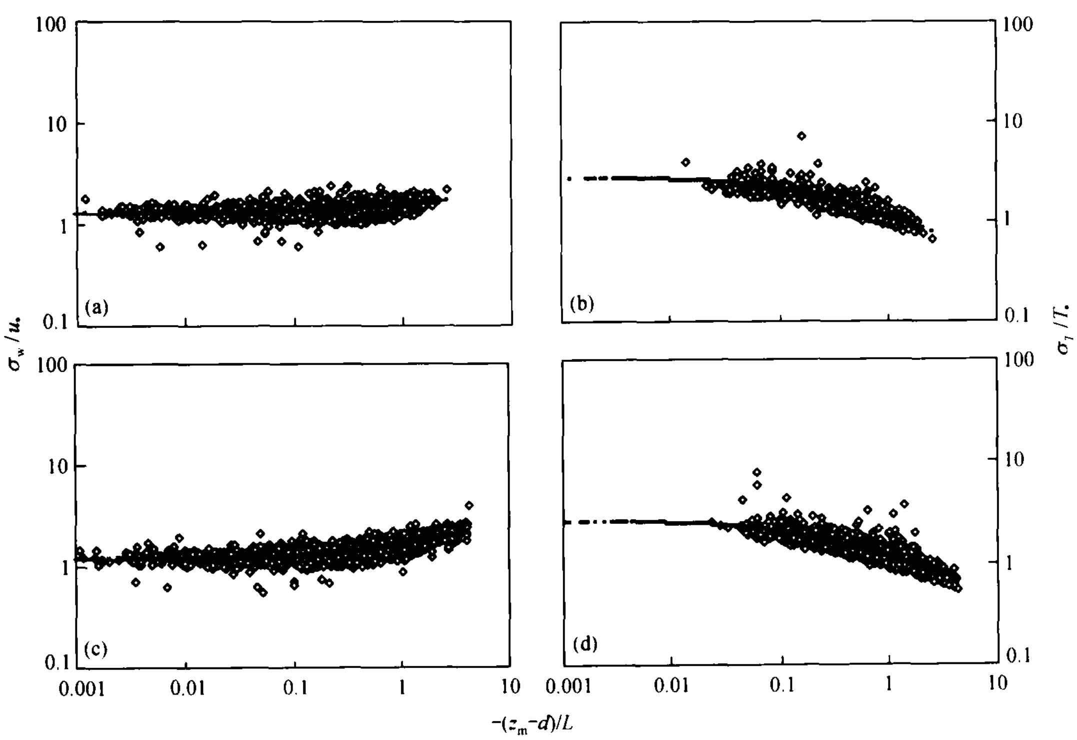

Fig. 4. The normalized standard deviation of vertical wind speed, σ_w/u_* (a) and (c), and temperature, σ_T/T_* (b) and (d), for unstable atmosphere stability, vs. stability, $-(z_m-d)/L$. z_m: 23.6 m for upper panel (a) and (b) and 39.6 m for under panel (c) and (d). The solid lines were the similarity functions determined by the nonlinear least squares.

Using eq. (1) mentioned above can describe σ_w/u_* well, not only for unstable conditions (fig. 4(a) and (c)) but also for stable conditions (neutral conditions). The nonlinear least squares determined values of the coefficient b_1=0.14≈1/7 at 23.6 m, less than the most often reported values of 1/3 over flat terrain, however, the coefficient b_1=0.24≈1/4 at 39.6 m was close to the most often reported values of 1/3 over flat terrain[22]. The values of the coefficient a_1 representing σ_w/u_* in purely mechanical turbulence of 1.28 (23.6 m) and 1.17 (39.6 m) were close to the 1.25 values reported for flat terrain independent of the surface cover[22].

This test cannot, however, be used for scalar fluxes in neutral conditions as the ratio σ_T/T_* is affected by too large relative errors[5]. In order to remove σ_T/T_* data measured under neutral conditions, we selected data for which $H > 100$ W m^{-2}, where H is the sensible heat flux density. Use of eq. (2) mentioned above described σ_T/T_* well for unstable conditions (fig. 4(b) and (d)). The nonlinear least squares determined values of the coefficient b_2 (–0.38≈–1/3 and –0.35≈–1/3, at 23.6 m and 39.6 m, respectively) were close to the most often reported values of –1/3 for flat terrain[22]. The values of the coefficient a_2 of 2.71 (23.6 m) and 2.59 (39.6 m) were close to the 2 values reported for flat terrain independent of the surface cover[22].

In all cases, the agreement between the measured values and the theoretical prediction is satisfying (fig. 4). The agreement of vertical velocity variance with the theoretical predictions suggested that no additional mechanical turbulence due to obstacles or instrumental distortion perturbed our turbulence flux measurements. The agreement of temperature variances with the theory predictions suggested that an inhomogeneity in the surface temperature and moisture conditions was of little impact on the data quality. The results implied that the turbulent flux measurements made at two heights were within the surface layer[22,24]. Although the land-surface conditions cannot fully meet the demand by the EC technique at the studied site, our measurements are valid and representative of the site.

2.3 Nocturnal turbulence fluxes

There is some likelihood that, during stable nighttime conditions, CO_2 exchange is underestimated by the EC measurements, even when storage of CO_2 below the EC systems is included. This is supported by the apparent correlation between friction velocity u_* (used as a measure for turbulent mixing) and CO_2 efflux during the night[25]. Indeed, nighttime efflux resulting from ecosystem respiration is controlled mainly by temperature and soil water content; it should be independent of turbulence if correlation between u_* and temperature and soil water content are removed. Underestimation of the nighttime CO_2 flux is an example of a selective systematic error and as such can be a serious problem, particularly when long-term budgets are estimated by integration of short-term flux measurement[6,25,26].

Most often, nocturnal flux underestimation has been assessed indirectly using the magnitude of u_* as the criterion[24]. A way to correct for flux underestimation during stable nighttimes is to replace the measured fluxes by the simulated efflux by a temperature function derived during well-mixed conditions[5,6,25]. This analysis was only performed during the nighttime since during the daytime turbulent fluxes may be systematically underestimated not only because of low u_*, but also because of low available energy[24]. No dependence of any of the turbulence fluxes on available energy was found during the nighttime period[24]. Limits of $-2 \leqslant (z_m-d)/L \leqslant 1$ for σ_w/u_* were imposed since the free convective asymptotic form is reached at $(z_m-d)/L= -2$ and σ_w/u_* becomes poorly behaved and no longer responds to surface-layer scaling at $(z_m-d)/L \geqslant 1$[22]. The discrepancy between the measured σ_w/u_* and that predicted by M-O theory fell to less than 20% at both heights when u_* reached its threshold values of 0.2—0.3 m s^{-1}. This suggests the shortcoming of using a threshold u_* to reject EC fluxes since the threshold u_* depended on measurement heights[24]. Use of the difference between the measured σ_w/u_* and that predicted by M-O theory was independent of measurement heights and hence served as a more robust criterion. However, it was also a better way to determine the u_* threshold. By weighting the relative underestimation with the frequency distribution of the friction velocity, a relative loss of CO_2 efflux can be estimated. Even when storage of CO_2 below the EC systems is included, a relative loss of CO_2 efflux was estimated at between 4% and 36%[25].

Moreover, if systematic underestimation of CO_2 flux occurred at low u_*, then the other turbulent fluxes that depend on the same assumption and theory should also be systematically underestimated. Fig. 5(b) and (c) show that in agreement with fig. 5(a), systematic underestimation of both latent heat flux and sensible heat flux occurred when u_* was below the u_* threshold, corresponding to the measured σ_w/u_* within 20% of that predicted by M-O theory. In the application, it is necessary to exclude the turbulence flux measurement

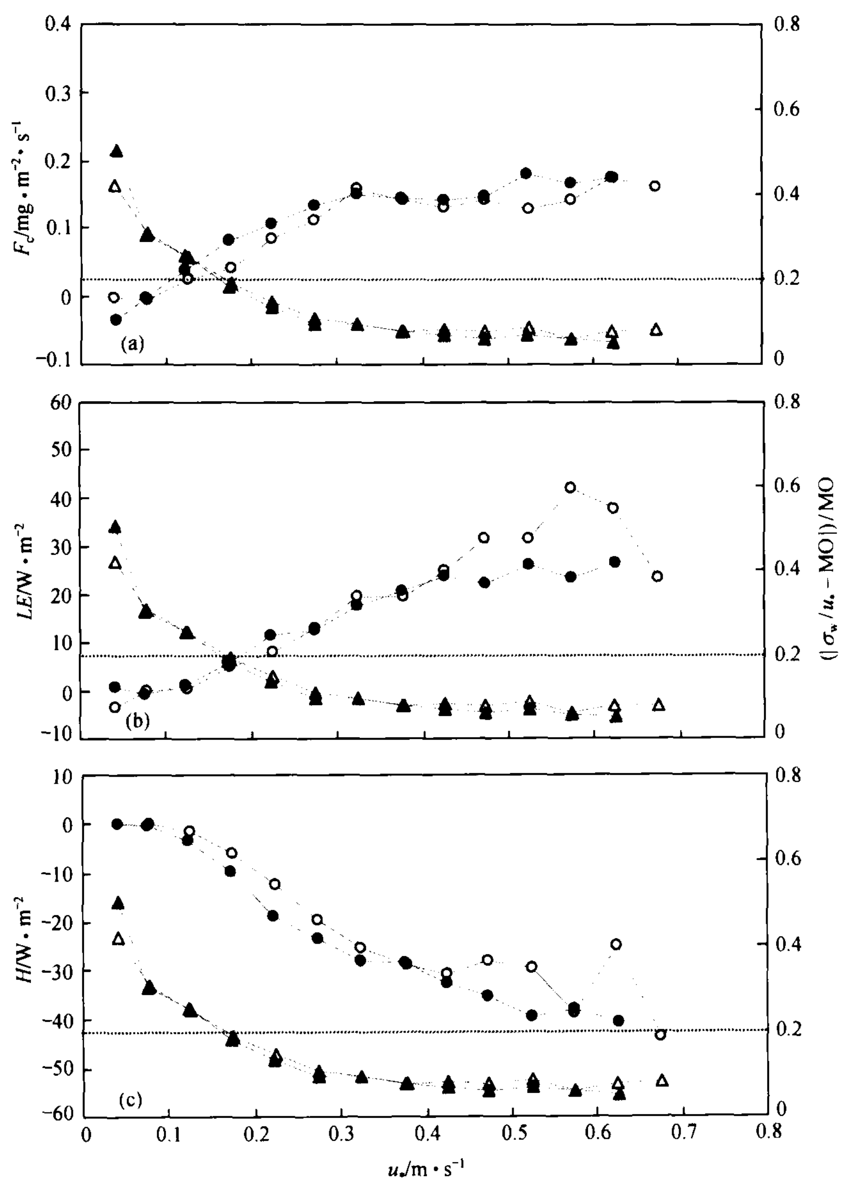

Fig. 5. Dependence of the CO_2 flux (F_c, (a)), latent heat flux (LE, (b)) and sensible heat flux (H, (c)) and turbulence homogeneity ($|\sigma_w/u_*-MO|/MO$) on the friction velocity (u_*) at night (Global radiation <1 W m^{-2}). Means were calculated corresponding to binned values of u_* at 0.05 m s^{-1} intervals.

data under low turbulent mixing[6,25,27].

2.4 Energy balance closure

A requirement that should be meet despite any ecological and climatological differences among the studied sites is the conservation of energy in the systems, according to the first law of thermodynamics. Thus, the closure of the energy balance is a useful parameter to check the plausibility of datasets obtained at different flux sites. In this approach, the sum of turbulent heat fluxes is compared with the available energy flux (the net radiation minus the storage flux densities in the observed ecosystem, including soil, air and biomass). If the energy terms balance each other, the quality of the flux data is considered to be sufficient. However, unclosed energy balance has been published for many studied sites covering either grassland or forests[10]. Non-closure of the energy balance is a common feature of the EC measurement above forest canopies with a mean imbalance in the order of 10%—30%[5,8,10,28].

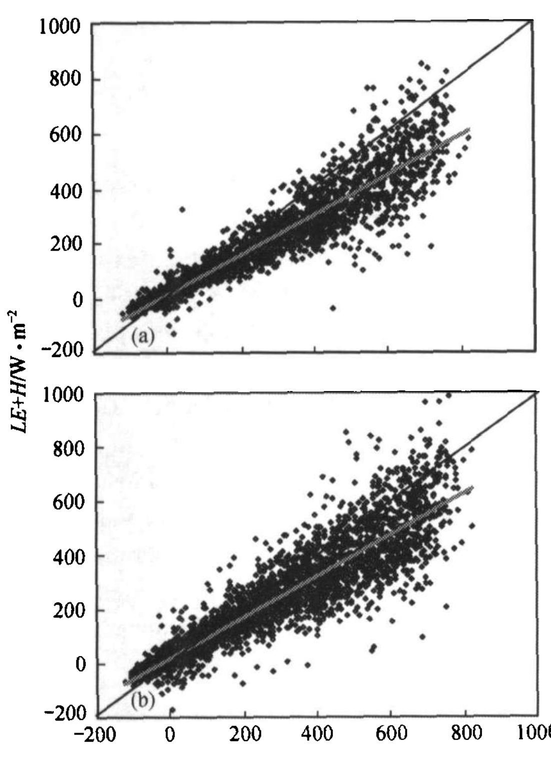

Fig. 6. The sum of the eddy covariance measurement of sensible and latent heat fluxes (H+LE) vs. the net radiation minus soil heat flux and heat storage in the air (R_n–G–S) for 23.6 m (a) and 39.6 m (b).

To represent the relative degree of energy balance closure in a dataset, the slope of a linear regression, s_1, and the slope of a linear regression forced through the origin, s_2, are used. This is necessary because the linear relationship between turbulent energy fluxes and available energy usually produces a significantly intercept[25]. Fig. 6(a) and (b) present the individual relationship between the turbulent energy fluxes and the available energy for turbulent flux measurement at two heights. In both cases, the slopes of a regular linear regression, s_1, 0.72 at 23.6 m and 0.76 at 39.6 m, are lower than that of the slopes of a linear regression forced to the origin, s_2, 0.75 at 23.6 m and 0.81 at 39.6 m. In both case a strong relation is found (r^2=0.88 at 23.6 m and r^2=0.85 at 39.6 m) but the sum of the eddy fluxes is systematically lower than the available energy. Energy balance closure at the studied site is between 72% and 81%, comparable with the imbalance in the order of 10%–30% in the literature[5,8,10,28]. These findings confirm the common observation that the energy balance tends to be more or less unclosed.

Non-closure of the energy balance could be due to several causes and does not necessarily indicate errors in the EC measurements only[5,10]. Table 1 summarizes the possible reasons for energy imbalance at FLUXNET sites and how these sources of error may affect energy balance closure and CO_2 fluxes[10]. The reasons for lack of closure across sites are not completely understood, but the following: (1) sampling errors. Plots of energy balance closure against wind direction showed no discernible pattern, indicating that lack of adequate fetch was not a factor. However, one of the most important causes of energy closure deficit in heterogeneous terrains is the mismatch of footprints of turbulent and non-turbulent fluxes. In addition, when the terrain is sloping, the flux measured by a horizontal radiometer gives a biased estimation of the flux really intercepted by the canopy, which is the main reason for the deficit between the different heights; (2) systematic instrument error including the turbulent and non-turbulent fluxes instruments; (3) low and high pass filtering. The instrument effects that damp the high-frequency fluctuations are the dynamic

Table 1 General list of possible reasons for energy imbalance at FLUXNET sites[10]

Cause of imbalance	Examples	*LE+H*	R_n–*G*–*S*	Ratio	Affecting CO_2
Sampling	Different source areas				No
Instrument bias	Net radiometer biased				If sonic or IRGA
Neglected energy sink	Storage above soil heat plates		+	–	No
High/low frequency loss	Sensor separation/large eddies	–		–	Yes
Advection	Regional				Yes

Also shown is whether this effect is expected to underestimate (–) or overestimate (+) the turbulent fluxes (*LE+H*), available energy (R_n–*G*–*S*) and the energy balance ratio (*LE+H*)/(R_n–*G*–*S*). The last column indicates whether this effect is relevant to interpretation of the CO_2 flux.

frequency response of the sonic anemometer and of the IRGA, the sensor response mismatch, the scalar path averaging, the sensor separation. The averaging period used to define mean fluxes can cut-off frequency contributions[25]; (4) neglected terms in the energy budget, such as storage flux densities in the observed ecosystem, including soil, air and biomass; and (5) mean advection (either horizontal or vertical) of scalar quantities. Advective effects are a major source of uncertainty, particularly in complex terrain, and they may not be fully quantified without the aid of 2- and 3-dimensional models. However, drainage flows are likely to be amenable to observational studies and more studies of CO_2 drainage should be performed[8]. It is likely that all possible biases can contribute to the observed energy budget deficit to some degree, although in varying magnitude. Thus, energy balance closure test was only used as a useful reference criterion and cannot be used to estimate the absolute error in the EC measurement[25,29].

3 Conclusions

The data quality of turbulent flux measurement by the EC technique at two and three canopy heights of a subtropical *Pinus* plantation on the red earth hilly region was assessed by three common criteria including the spectral analyses, integral turbulence test (flux variance similarity) and energy balance closure. Above-canopy power spectral slopes for all velocity components and scalars such as CO_2, H_2O and air temperature followed the expected −2/3 power law in the inertial subrange, and their cospectral slopes were close to −4/3 power law in the inertial subrange. The important contribution of large-scale motions to energy and mass transfer above the canopy at higher measurement level was confirmed by the spectral analysis. Computations of power spectra and cospectra indicated that the instrument response characteristics and its sampling rate were adequate for measuring fluxes above the forest canopy of two measurement heights.

The Monin-Obukhov similarity functions for the normalized standard deviation of vertical wind speed and air temperature were well-defined functions of atmospheric stability at two heights above the forest canopy and implied that measurements made at two heights were within the surface layer. Although the land-surface conditions cannot fully meet the demand by the EC technique, our measurements are valid and representative of the site.

Nocturnal flux underestimation and departures of this normalized standard deviation of vertical wind speed similarity function from that expected from Monin-Obukhov theory were a function of friction velocity. As for the subtropical *Pinus* plantation, an optimal criterion of friction velocity was found to be greater than 0.2—0.3 $m\ s^{-1}$ for nocturnal fluxes so that the EC flux measurement was under high turbulent mixing conditions. Energy balance closure reached about 72%—81% above the threshold values of friction velocity, which was comparable to the 10%—30% of energy imbalance reported in the literature. But the energy balance closure test was only used as a useful reference criterion.

The EC system has the ability to resolve fluctuations associated with small eddies and did not induce an obvious underestimation of the measured turbulent flux at two heights. However, some of the meteorological limitations include large footprints, gravity

waves, advection, and aerodynamic or low turbulence issues resulted in the invalid assumption of the EC technique.

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