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The impact of averaging period on eddy fluxes observed at ChinaFLUX sites

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Abstract

In this paper, the 'ensemble block' time average procedure and the Ogive function are applied to three ChinaFLUX sites to determine the low-frequency contribution to eddy fluxes. It is found that both methods give similar results. They show that 30 min flux-averaging periods are sufficient to capture all flux scales over a wheat field, but 60 min or longer is necessary over forests. Our results show that the optimal averaging period is a site-specific parameter. According to this analysis, for some ChinaFLUX sites at least, an averaging period that captures the low-frequency transport may improve the energy balance problem.

Keywords: Terrestrial carbon cycle; Eddy covariance; Averaging period; Low-frequency contribution

1. Introduction

Eddy covariance is a micrometeorological technique that allows a non-invasive measurement of the exchange of CO_2 between the atmosphere and a several hectare area of forest, shrubland, or grassland (Baldocchi et al., 1988; McMillen, 1988). With the establishment of an international network, FLUXNET (Baldocchi et al., 2001), we now have available a large body of data on terrestrial ecosystem exchange of mass and energy that are integrated at the stand level (Wofsy et al., 1993; Valentini et al., 2000; Wilson et al., 2002). Most of these long-term experiments are intended to monitor the annual exchange of CO_2 between the atmosphere and vegetated surfaces to increase our understanding of the terrestrial carbon cycle (Baldocchi, 2003). However, investigators must first establish that the accuracy and precision of eddy covariance is sufficient to allow a reliable assessment of carbon sequestration over time scales ranging from hours to decades. The errors can be broadly divided into those caused by instrument limitations (Moncrieff et al., 1996; Massman and Lee, 2002) and those that result from the assumptions about the turbulent flow field that are embodied in the data analysis techniques (Lee, 1998; Finnigan, 1999; Finnigan et al., 2003). A significant number of the experimental sites in FLUXNET are situated in complex terrain and so their measurements may be subject to the sources of errors noted above.

The lack of energy balance closure in eddy covariance studies is a widespread feature of flux measurements over forests (Wilson et al., 2002), suggesting the presence of a widespread problem, whether instrumental or methodological. However, problems with lack of energy balance closure have also been reported from sites that approach horizontally homogeneous conditions (Aubinet et al., 2000; Wilson et al., 2002). One possible explanation is that latent and sensible heat flux is being missed by the flux measurement, through inadequate sampling of the frequency domain. The importance of low-frequency

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motions to energy and carbon balance studies have been highlighted in recent papers (Mahrt, 1998; Sakai et al., 2001; Finnigan et al., 2003). Finnigan et al. (2003) demonstrated that over tall canopies on flat ground in convective conditions, or on hilly sites in near neutral flow, the scalar cospectra have much more low-frequency content than the classical surface layer spectral forms would predict. The filtering of this low-frequency covariance by the averaging-rotation operations in common use is a large contributory factor to the failure to close the energy the energy balance over tall canopies (Sakai et al., 2001; Finnigan et al., 2003). At some sites, however, inclusion of low-frequency transport does not actually improve energy balance closure (Malhi et al., 2004).

The objective of this paper is to investigate the optimal choices of averaging period for eddy flux computation at ChinaFLUX sites. Since its establishment in 2002, ChinaFLUX has adopted 30-min as the averaging period for the online flux computation. While this is an averaging period used in many surface–air exchange investigations, several recent studies suggest it may be too short to capture the role of low-frequency contributions. This paper is motivated by the need to clarify the role of low-frequency contributions to eddy fluxes, providing some insight into the energy and carbon balance studies in ChinaFLUX.

A second motivation of our study is related to the fact that the subject of low-frequency transport falls in the still poorly understood field of self-organized turbulence structures and mesoscale flows. Even though it does not provide much theoretical insight, our study contributes to this area of ongoing research by focusing on sites in the Asian monsoon region. Previous studies suggest that local climatic conditions could play a role in the choice of the optimal averaging period. For example, Malhi et al. (2004) demonstrated that low-frequency transport is much less important at a forest site in marine climate than at a site influenced by deep convection in the tropics and perhaps also at a site in the humid temperate climate in New England, U.S.A. (Sakai et al., 2001). Any future synthesis study that attempts to resolve this issue is possible only if experimental investigations span a wide range of site and climatic conditions.

2. Sites and data analysis

2.1. Sites

In this study, we used data from three ChinaFLUX sites: Yucheng cropland, Qianyanzhou subtropical *Pinus* plantation and Changbaishan temperate broad-leaved Korean pine mixed forest (Table 1). The eddy covariance instruments were the same at all three sites, consisting of a three-dimensional sonic anemometer (model CSAT-3, Campbell Scientific Inc., Logan, Utah) and an open-path H_2O/CO_2 analyzer (model LI-7500, Li-Cor Inc., Lincoln, Nebraska). More extensive description of the sites can be found in Wen et al. (2006) and Yu et al. (2006).

2.2. Data analysis

The flux of CO_2 is given by

$$F_c = \overline{w'\rho'_c} \tag{1}$$

where w' and ρ'_c are the vertical wind speed and CO_2 concentration fluctuations around the means, respectively, and the overbar represents a time average. Fluxes of sensible heat, H, and latent heat, LE, are calculated in the same manner. A three-dimensional rotation of the coordinate system was applied to the wind components to remove the effects of instrument tilt or irregularity of the airflow (Kaimal and Finnigan, 1994; Aubinet et al., 2000). Corrections were made for the effects of fluctuations in air density on the fluxes of CO_2 and water vapour (Webb et al., 1980). The data have not been corrected for high frequency losses (see Moore, 1986; Aubinet et al., 2000; Wen et al., 2005).

Table 1
Summary of site characteristics

Site	Yucheng	Qianyanzhou	Changbaishan
Location	36°50′N, 116°34′E	26°44′N, 115°03′E	42°24′N, 128°05′E
Altitude (m)	28	102	738
Terrain	Flat plain	Hilly region	Flat plateau
Climate	Temperate monsoon	Subtropical monsoon	Temperate monsoon
Vegetation	Winter wheat, summer maize	Pine plantation	Temperate mixed forest
Stand height (m)	–	12	26
Stand age (year)	–	20	200
Measurement height (m)	2	23	40

It is recognized that corrections for the low-frequency flux loss cannot be made in reference to some standard spectra and cospectra because the best known of the spectra models (Kaimal et al., 1972) were obtained over short vegetation surfaces and not necessarily appropriate to use over tall forests. Operationally, the role of the low-frequency transport is accounted for by choosing an optimal averaging period. The choice is decided by the 'ensemble block time averaging' method (method 1; Sakai et al., 2001; Finnigan et al., 2003; Malhi et al., 2004) and the Ogive method (method 2; Berger et al., 2001). Both methods were deployed in this study. Briefly, in method 1, fluxes recomputed using a range of averaging periods are compared with those made with a "standard" averaging period (in this case, 30 min). An optimal averaging period is decided by examining the asymptotic behavior of the flux ratio against the averaging period.

In method 2, the choice of an averaging period is normally based on cumulative flux from the integrated cospectra of scalar c and vertical velocity w, Co_{wc} (e.g., Berger et al., 2001), as

$$\mathrm{Og}_{wc}(f) = \int_{f_{\mathrm{high}}}^{f} \mathrm{Co}_{wc}(f)\,\mathrm{d}f \tag{2}$$

where f_{high} is the Nyquist frequency, and f is no smaller than the lowest resolvable frequency $f_{\mathrm{low}} = (2T)^{-1}$. Here T is the length of the time series. The Ogive of all frequencies is equal to the covariance of the corresponding time series. Ogives that have an asymptotic shape toward the highest and lowest frequencies suggest that all flux-carrying scales are constrained in the sampling period.

3. Results and discussion

3.1. Effects of averaging periods over wheat canopy

Fig. 1 presents the changes of daytime-averaged F_c and (H + LE) with different averaging periods ranging from 1 to 720 min for 6 individual days at the Yucheng site. The absolute value of the flux density increases rapidly as the averaging period changes from 1 to 15 min, then remains stable until about 120 min. Further increase in the averaging period caused significant variability in the data. When record lengths are too short to obtain an adequate sample of the transport, it may lead to significant systematic errors. Attempts to reduce the systematic errors by increasing the record length may capture significant non-stationary or heterogeneity (Mahrt, 1998; Foken and Wichura, 1996). The large variety of fluxes estimates with averaging time greater than 120 min is probably result of non-stationary status. Therefore, care must be taken to avoid averaging regimes that exceed the time over which flow is stationary (Berger et al., 2001).

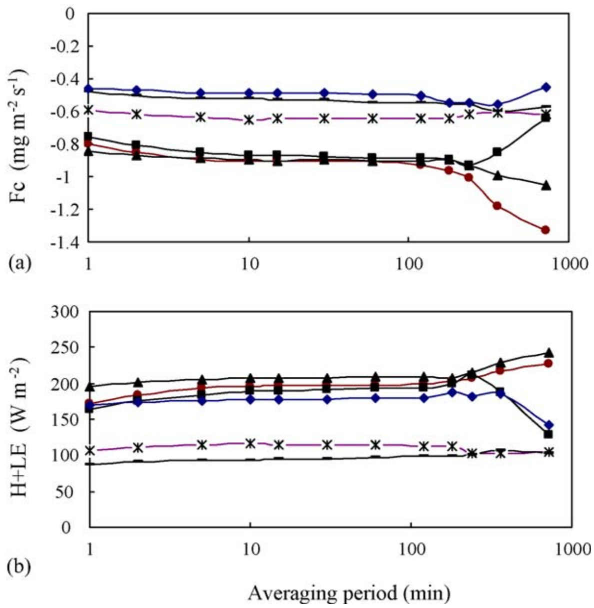

Fig. 1. Carbon dioxide (F_c, a) and latent heat plus sensible heat fluxes (H + LE, b) calculated with different averaging periods from 1 to 720 min at the Yucheng site. Each line represents observation over 1 day, April 2003.

Table 2 provides regression equations and statistics of the averages recomputed with different averaging time at the Yucheng site for a period of 15 days in May 2003. In comparison with the fluxes computed over 30 min intervals, the 1-min averaging period was obviously too short, resulting in a negative flux bias of 12%. The flux bias became very small when the averaging period was 5 min or longer. Thus, an averaging period of 30 min appears adequate for this site.

The contribution of eddies with period greater than 5 min is surprisingly small compared to other studies (e.g., Sakai et al., 2001), and cannot be explained by the low measurement height (Table 1) because low-frequency eddies are thought to be generated by mechanisms outside the surface layer (Malhi et al., 2004). To seek an explanation for this, we note that the site is located in the wheat-farming region of the North China Plains. Because the climate during the wheat-growing season is dry, irrigation is widespread, creating a moist lower atmospheric boundary layer in an otherwise dry climate (Lee et al., 2004). It is possible that the reduced sensible heat flux due to irrigation may have suppressed low-frequency convective motions.

Table 2
Statistics of fluxes recomputed with different averaging period

Fluxes	Averaging time (min)	Regression equation	R^2	Mean	Relative bias (%)
F_c (mg m^{-2} s^{-1})	1	$y = 0.878x - 0.005$	0.9757	−0.498	−11.70
	5	$y = 0.9648x - 0.0126$	0.9911	−0.553	−1.95
	10	$y = 0.9814x - 0.0133$	0.9917	−0.557	−1.24
	15	$y = 0.9921x - 0.0041$	0.9937	−0.562	−0.35
	30	$y = x$	1	−0.564	0.00
	60	$y = 0.9907x - 0.0203$	0.9825	−0.569	0.89
	120	$y = 0.9847x - 0.0368$	0.9795	−0.57	1.06
H + LE (W m^{-2})	1	$y = 0.8739x - 0.5512$	0.97465	157.1	−12.82
	5	$y = 0.9739x - 0.4221$	0.9932	174.6	−3.11
	10	$y = 0.9887x + 0.1082$	0.99535	178.4	−1.00
	15	$y = .9999x - 0.8195$	0.9966	178.6	−0.89
	30	$y = x$	1	180.2	0.00
	60	$y = 0.9995x + 2.3906$	0.9968	181.4	0.67
	120	$y = 0.9974x + 3.037$	0.9958	181.9	0.95

All results are compared with the flux with a 30 min averaging period. Data are observed at the Yucheng site for 15 days, May 2003.

3.2. Low-frequency contribution to eddy fluxes over forests

Fig. 2 compares F_c and (H + LE) calculated with various averaging periods at the Qianyanzhou site for 10 days. The ordinate is the 60 min or 120 min ensemble-averaged flux, and the abscissa is the arithmetic average of corresponding several 30 min block-averaged. Also included in Fig. 2 are linear regression equations of them and the coefficient of determination (R^2). The fluxes with an averaging period of 60 min are 4–6% higher than those with the 30 min averaging period. In comparison, the fluxes with a 120 min averaging period are only 1.5 and 2% larger than those with the 30 min

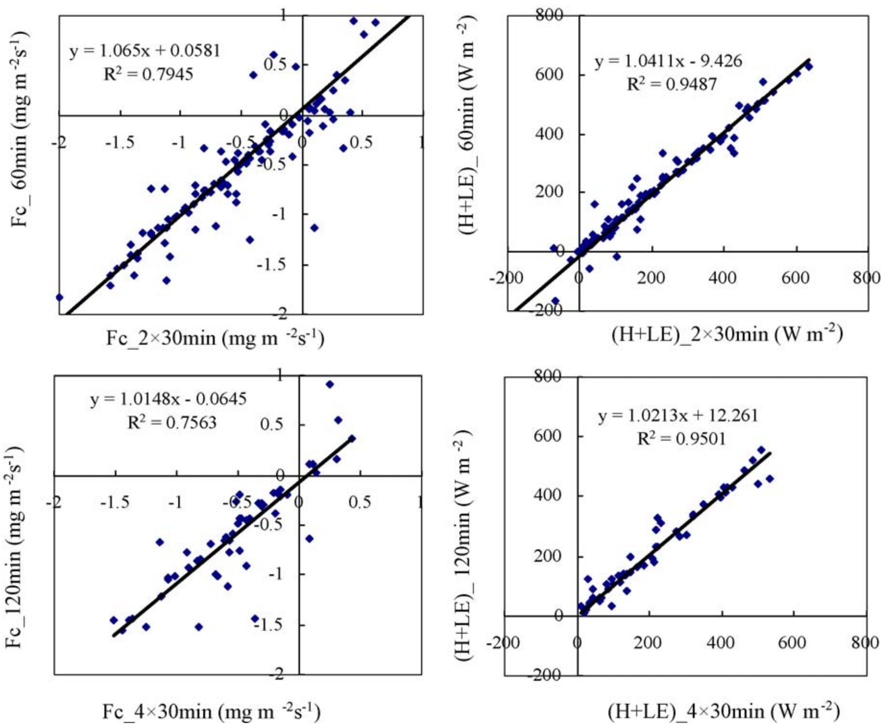

Fig. 2. Comparison of carbon dioxide (F_c) and the sum of latent heat and sensible heat fluxes (H + LE) calculated with 60 and 120 averaging periods against the fluxes with the 30 min averaging period at the Qianyanzhou site, June 2003.

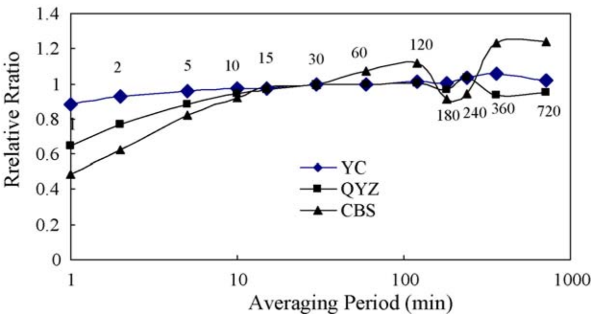

Fig. 3. Ratio of latent heat and sensible heat fluxes (H + LE) calculated with different averaging periods from 1 to 720 min to the 30 min (H + LE) fluxes at the Yucheng (YC), Changbaishan (CBS) and Qianyanzhou (QYZ) sites.

averaging period, suggesting that the optimal averaging period at this site is probably close to 60 min but not as long as 120 min. Similar results are also observed for the Changbaishan site.

In Fig. 3, we present the sum of latent heat and sensible heat fluxes (H + LE) calculated with different averaging periods and normalized by the 30 min fluxes at the Yucheng, Changbaishan and Qianyanzhou sites. The low-frequency transports at these three ChinaFLUX sites have very different characteristics. At the Yucheng site, (H + LE) with the 1 and 10 min averaging periods are 10 and 2% lower than that with the 30 min averaging period, respectively. On the other hand, at the Changbaishan and Qianyanzhou sites, (H + LE) with the 1 and 10 min averaging periods are substantially lower than that with the 30 min average. At these two forest sites, the fluxes with an averaging period greater than 30 min are usually higher than those of the 30 min averaging period, consistent with the data presented in Fig. 2. In all three sites, if averaging periods are longer 120 min, the results become unstable, which is a weakness of the ensemble block averaging method.

3.3. Results of the Ogive analysis

Fig. 4 is an Ogive plot for the kinematic sensible heat flux at three sites in the daytime. The longest averaging period we selected is 120 min. Lines in each panel represent consecutive sample periods of 120-min from 6:00 to 18:00 h local time. It is clear that, even at the same site, the asymptotic threshold frequency below which the Ogive curves are flat changes is not the same during different periods of a day. However, the within-day variations are smaller compared to the variability across the sites.

The difference among the three sites is best shown by the daytime-averages of the Ogive values for sensible

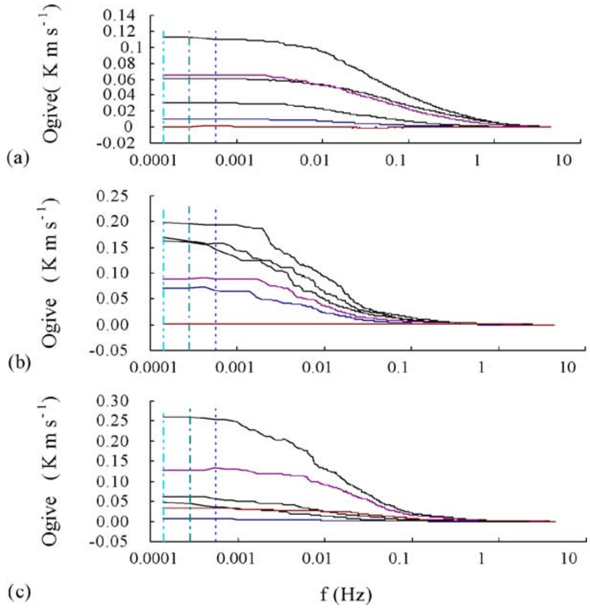

Fig. 4. Ogives for the daytime kinematic sensible heat flux at Yucheng (a), Changbaishan (b) and Qianyanzhou (c) sites. The dashed vertical lines, from right to left, correspond to averaging periods of 30, 60 and 120 min, respectively. Lines in each panel represent 120 min sample periods.

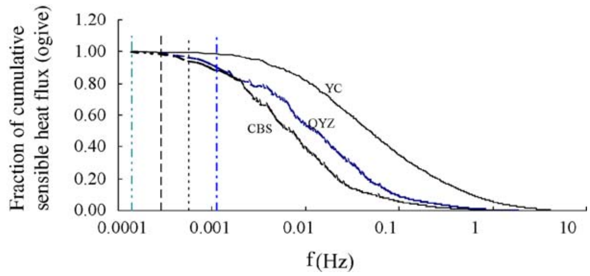

Fig. 5. Comparison of daytime-averaged Ogive values for the kinematic sensible heat flux (normalized by the 120 min kinematic sensible heat flux) at Yucheng (YC), Changbaishan (CBS) and Qianyanzhou (QYZ) sites. The dashed vertical lines, from right to left, correspond to averaging periods of 15, 30, 60 and 120 min, respectively.

heat flux at the three sites, as shown in Fig. 5. For the Yucheng site, the optimal averaging period can be as short as 10–15 min (0.0017–0.0011 Hz) without a significant loss of the low-frequency contribution. This is consistent with the conclusion drawn from the ensemble block averaging method discussed above. For the Qianyanzhou and Changbaishan sites, the appropriate averaging period should be at least 60 min.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, P., Martin, P., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenster, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. Adv. Ecol. Res. 30, 113–174.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biol. 9, 479–492.

Baldocchi, D.D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, U.K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415–2434.

Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.

Berger, B.W., Davis, K.J., Yi, C., Bakwin, P.S., Zhao, C.L., 2001. Long-term carbon dioxide fluxes from a very tall tower in a northern forest: flux measurement methodology. J. Atmos. Ocean. Technol. 18, 529–542.

Finnigan, J., 1999. A comment on the paper (1998): ‘‘On micrometeorological observations of surface–air exchange over tall vegetation’’. Bound.-Lay. Meteorol. 97, 55–64.

Finnigan, J., Clement, R., Malhi, Y., Leuning, R., Cleugh, H.A., 2003. A re-evaluation of long-term flux measurement techniques. Part I. Averaging and coordinate rotation. Bound.-Lay. Meteorol. 107, 1–48.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. Forest Meteorol. 78, 83–105.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y., Cote, O.R., 1972. Spectral characteristics of surface layer turbulence. Q. J. Roy. Meteorol. Soc. 98, 563–589.

Kaimal, J.C., Finnigan, J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, New York, pp. 255–261.

Lee, X., 1998. On micrometeorological observations of surface–air exchange over tall vegetation. Agric. Forest Meteorol. 91, 39–49.

Lee, X., Yu, Q., Sun, X.M., Liu, J.D., Min, Q.W., Liu, Y.F., Zhang, X.Z., 2004. Micrometeorological fluxes under the influence of regional and local advection: a revisit. Agric. Forest Meteorol. 122, 111–124.

Mahrt, L., 1998. Flux sampling errors for aircraft and towers. J. Atmos. Ocean. Technol. 15, 416–429.

Malhi, Y., McNaughton, K., Randow, C.V., 2004. Low-frequency atmosphere transport and surface flux measurements. In: Lee, X., Massman, W., Law, B. (Eds.), Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis. Kluwer Academic Publisher, Dordrecht, pp. 101–118.

Massman, W.J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long term studies of carbon and energy exchanges. Agric. Forest Meteorol. 113, 121–144.

McMillen, R.T., 1988. An eddy correlation technique with extended applicability to non-simple terrain. Bound.-Lay. Meteorol. 43, 231–245.

Moncrieff, J.B., Malhi, Y., Leuning, R., 1996. The propagation of errors in long-term measurement of land-atmosphere fluxes of carbon and water. Global Change Biol. 2, 231–240.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Bound.-Lay. Meteorol. 37, 17–35.

Sakai, R.K., Fitzjarrald, D.R., Moore, K.E., 2001. Importance of low-frequency contributions to eddy fluxes observed over rough surfaces. J. Appl. Meteorol. 40, 2178–2192.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., GuÖmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Webb, E.K., Pearman, G.L., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. Roy. Meteorol. Soc. 106, 85–100.

Wen, X.F., Yu, G.R., Sun, X.M., Li, Q.K., Liu, Y.F., Zhang, L.M., Ren, C.Y., Fu, Y.L., Li, Z.Q., 2006. Soil moisture effects on the temperature dependence of ecosystem respiration in a subtropical *Pinus* plantation of southern China. Agric. Forest Meteorol. 137, 166–175.

Wen, X.F., Yu, G.R., Sun, X.M., Liu, Y.F., 2005. Turbulence flux measurement above the overstory of a subtropical *Pinus* plantation over the hilly region in southeastern China. Sci. China Ser. D 48 (Supp. I), 63–73.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Valentini, R., Verma, S., Meyers, T., Moncrieff, J., Monsonn, R., Oechel, W., Tenhunen, J., 2002. Energy balance closure at FLUXNET sites. Agric. Forest Meteorol. 113, 223–243.

Wofsy, S.C., Goulden, M.L., Munger, J.W., Fan, S.M., Bakwin, P.S., Daube, B.C., Bassow, S.L., Bazzaz, F.A., 1993. Net exchange of CO_2 in a mid-latitude forest. Science 260, 1314–1317.

Yu, G.R., Wen, X.F., Sun, X.M., Tanner, B.D., Lee, X., Chen, J.Y., 2006. Overview of ChinaFLUX and evaluation of its eddy covariance measurement. Agric. Forest Meteorol. 137, 125–137.