Determination of averaging period parameter and its effects analysis for eddy covariance measurements

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Abstract It is more and more popular to estimate the exchange of water vapor, heat and CO_2 fluxes between the land surface and the atmosphere using the eddy covariance technique. To get believable fluxes, it is necessary to correct the observations based on the different surface conditions and to determine relevant techinical parameters. The raw 10 Hz eddy covariance data observed in the Yucheng and Changbai Mountains stations were recalculated by various averaging periods (from 1 to 720 min) respectively, and the recalculated results were compared with the results calculated by the averaging period of 30 mins. Meanwhile, the distinctions of fluxes calculated by different averaging periods were analyzed. The continuous 15 days observations over wheat fields in the Yucheng station were mainly analyzed. The results are shown that: (i) In the Yucheng station, compared with the observations by 30 min, when the averaging period changes from 10 to 60 min, the variations of the eddy-covariance estimates of fluxes were less than 2%; when the averaging period changes less than 10 min, the estimate of fluxes reduced obviously with the reduction of the averaging period (the max relative error was −12%); and when the averaging period exceeds 120 min, the eddy covariance estimates of fluxes will be increased and become unsteady (the max relative error is over 10%); (ii) the eddy covariance estimates of fluxes over wheat field in the Yucheng station suggusted that it is much better to take 10 min as an averaging period in studying diurnal change of fluxes, and take 30 min for a long-term flux observation; and (iii) normalized ratio was put forward to determine the range of averaging period of eddy covariance measurements. By comparing the observations over farmlands and those over forests, it is indicated that the increase of eddy covariance estimates over tall forest was more than that over short vegetation when the averaging period increased.

Keywords: eddy covariance, various surface conditions, averaging period, parameter, ChinaFLUX.

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Since the 1980s, scientists have presumed that there is probably missing sink in terrestrial biosphere and inshore continental shelf, and also regarded the increase of CO_2 concentration as a significant cause of global warming. So accurate observations and estimates of CO_2 absorption and emission have been the focus of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol and the focus of global change research[1,2]. To estimate carbon absorption and emission in various ecosystems more precisely, many networks of CO_2 flux were established in western countries[3—6], and at the same time or later, observation and research in this field were performed systematically in China[7−16]. Eddy covariance technique is more and more widely used in long-term observations as a result of its fast development, which takes a significant effect on surface fluxes research. Recently, the study on the exchange of water vapor, heat and CO_2 between land surface and atmosphere using eddy covariance technique were developed greatly in China. Especially, the establishment of ChinaFLUX in 2002 promoted the study capacity of China. To get reliable observations of various ecosystems and surface conditions, some key problems encountered when using eddy covariance technique must be solved. Although at present eddy covariance technique is recognized as the best method for measuring land surface fluxes, the error and uncertainties of flux estimates are still great, if it is used incorrectly and without necessary corrections. By analyzing the observations in 22 stations of FLUXNT, Kell Wilson et al.[17] found that the failure of energy balance closure was fairly common, including all types of vegetation and climate (the Mediterranean climatic zone, the temperate climatic zone and the polar region climatic zone), and the energy unbalance is up to 20% of the available energy. Massman et al.[18] analyzed the uncertainties of eddy covariance and pointed out the primary sources of error. They are (i) instruments relevant parameters (such as time response constant) and field installation problems[19,20]; (ii) sampling (sampling frequency and averaging period)[21,22]; (iii) power spectral and cospectral features of wind speed and other physical quantities, and the attenuation of high and low frequency[23]; (iv) the influences of concentration change on eddy covariance estimates of CO_2 flux[24]; (v) advection correction and the coordinate system transformation[25—27]; and (vi) the effects of gravity wave, nighttime fluxes and other problems[19]. Lately Finnigan[27] derived a new conclusion based on some measurements over forests. He thought that the averaging period for calculating fluxes over forests should be longer (e.g. 2—4 h) than the usual time interval (e.g. 30 min), as the contribution of low frequency to the fluxes will be lost when averaging period is too short. Therefore, how do we determine averaging period parameter in practice when using eddy covariance technique over homogenous and heterogeneous surfaces (e.g. wheat fields and forest)? This paper analyzes the influences of different averaging period parameters on eddy covariance estimates of fluxes, and determines the appropriate threshold of averaging period for calculating fluxes in specific conditions.

1 Theories and methods

1.1 Eddy covariance technique

For a specific scalar s, its vertical flux F can be expressed as

$$F = \rho_a \overline{w's'}, \tag{1}$$

where ρ_a is the air density, w is vertical velocity, the prime symbol denotes an instantaneous departure from the mean, the overbar denotes the average. For a specific period T, F can be obtained by calculating the integral of the covariance of s and w during period T.

$$F = \rho_a \frac{1}{T}\int_0^T (w_i'(t)s_i'(t))\mathrm{d}t. \tag{2}$$

In practice, due to the discrete raw data only, the calculating equation will become

$$F = \rho_a \frac{1}{N}\sum_{i=1}^{N}(w_i'(t)s_i'(t)), \tag{3}$$

where N is the product of sampling rate (f) and averaging period (T), that is $N=T\times f$.

In practical situations, f and T usually range from 5 to 20 Hz and from 10 to 40 min, respectively. In theory, the higher the sampling frequency is, the longer the averaging period is, and the closer the measurement to the actual value will be. Nevertheless, the higher the sampling frequency is, the bigger data saving capacity is needed, which will result in higher research cost and or needs newer technology. On the one hand, if the averaging period is too long, some specific changes contained in the surface fluxes will be missed out; the mean value contains a long-time uncertainty or trend, and the trend will influence the calculated fluxes. Therefore, when determining the averaging period, it should be short enough to guarantee the stationary of data series, and meanwhile, it should be long enough to include the slower fluctuation of the turbulent spectrum (low frequency contribution). That is the problem to be discussed in this paper, which has been paid attention by the international researchers.

To test the effect of averaging periods, two averaging methods, block time average and ensemble block time average[27] were applied.

The simplest and most widely used time averaging is the 'block' average, which is commonly used to calculate fluxes real-time.

$$\overline{s(t)} = \int_0^T (s(t))\mathrm{d}t. \qquad (4)$$

All averaged variables, such as s, are constant over the time interval T so that the block averaging operation formally obeys the Reynolds averaging rules, and

$$s(t) = \overline{s} + s'(t), \qquad (5)$$

$$w(t) = \overline{w} + w'(t), \qquad (6)$$

$$\overline{w(t)s(t)} = \overline{w}\,\overline{s} + \overline{w's'}. \qquad (7)$$

Note that any deterministic trends or low frequency components in the record are contained.

The "ensemble block time average" is a formal averaging procedure, because it describes the way in which block averaged or filtered data from finite averaging periods of length T are composited to form a long-term mass balance[27]. We will use caret brackets $\langle\ \rangle$ to denote the block ensemble and the procedure forms the arithmetic mean of a series of block averaged quantities.

$$\langle\overline{s}\rangle = \frac{1}{N}\sum_{n=1}^{N}\overline{S}_n. \qquad (8)$$

The instantaneous value of a variable has been recorded over many time intervals, and each of length T can be decomposed into

$$s_n\langle t\rangle = \langle\overline{s}\rangle + \overline{s}_n' + s'(t), \qquad (9)$$

$$\langle\overline{w(t)s(t)}\rangle = \langle\overline{ws}\rangle = \langle\overline{w}\rangle\langle\overline{s}\rangle + \langle\overline{w}'\overline{s}'\rangle + \langle\overline{w's'}\rangle. \qquad (10)$$

Here, $\langle\overline{w}'\overline{s}'\rangle + \langle\overline{w's'}\rangle$ is the block-ensemble averaged covariance computed from N periods T, it is precisely equal to the simple block-averaged eddy covariance that would be computed if we changed the averaging period from T to the total period $N \times T$. eq. (9) describes the relationship between two results. It implies that the covariance of w and s calculated during a longer period ($N \times T$) is not equal to the arithmetic mean of the covariance obtained during many short periods (T).

1.2 Theoretic method for determining the averaging period

Based on the fact that eddy covariance technique is used to measure CO_2 and H_2O fluxes between the vegetation and the atmosphere, ChinaFLUX should take both the ecological and micrometeorological relevant principles into account to determine the appropriate averaging period. It should (i) distinguish the characteristics of daily changes in CO_2 and H_2O flux; (ii) distinguish the effects of sporadic incident in a short cycle; and (iii) gain the most component of low- frequency fluxes. Kaimal and Finnigan[28] put forward a simple method for calculating averaging period parameter, i.e.

$$T \cong \frac{2\sigma_\alpha^2\tau_\alpha}{\overline{\alpha}^2\varepsilon^2}, \qquad (11)$$

where σ_α is the ensemble variance of the scalar α, τ is an integral time scale, ε is an acceptable level of error. According to eq. (11), T should be changed with the atmospheric status, but it is unpractical in online calculation, so we must appoint an appropriate averaging period first. Kaimal and Finnigan[28] gave some reference of the parameters. For typical daytime, σ_u=1 m

s^{-1}, $\tau_u = 10$ s, $\varepsilon = 0.02$, $u = 5$ m s^{-1} and so $T \approx 2000s \approx$ 30 min. In ChinaFLUX, the averaging period of online calculation is 30 min. On the basis of estimation above, the averaging period of 30 min should be suitable for the most conditions. However, because the mean vertical velocity during a period is not equal to zero in most conditions (of course, it can be corrected partially by using coordinate transformation), according to eq. (10), the covariance of them in a longer period (ensemble block time average) is not equal to the arithmetical mean of covariance in several shorter periods (block time average). It implies that the choice of averaging period will influence the final results of fluxes. In most micrometeorological experiments the averaging period T is chosen for experimental convenience, with typical values 15—30 min. Here, what we are interested in is what will happen if the averaging period is very short (e.g. 1—2 min) or very long (e.g., 2—6 h).

In order to verify the influences of various averaging period parameters on flux estimates, 1, 2, 5, 10, 15, 20, 30, 60, 120, 180, 240, and 720 min were adopted as averaging period, respectively. Although taking 1, 2, 5 and 720 min as averaging period is impractical to estimate fluxes, it can help us to understand the problem. Nowadays internationally, a pattern of 10 Hz sampling frequency and 30 min averaging period are adapted usually. This paper assumes that the pattern above is the "criterion" for the comparison between fluxes calculated by different averaging periods, by comparing the fluxes calculated by various averaging periods with the fluxes calculated by criterion averaging period, the influences of different averaging periods on flux estimates can be understood.

2 Locations, instruments and materials

In this paper, the data we used are all from the two observation stations of ChinaFLUX with different surface conditions. They are: (i) Yucheng integrated experimental station (36°50′N, 116°34′E, altitude is 28 m), which is in flat terrain and open surround, and it belongs to homogeneous surface basically. The measurements were performed during the wheat growing seasons. (ii) Changbai Mountains forest experimental station (41°24′09″N, 128°05′45″E, altitude is 761 m), where the domain trees are red broadleaf pinewoods, the land slope of forest is no more than 4%, it is temperate continental climate of mountain region influenced by monsoon, and the annual precipitation is 632.8—782.4 mm.

The instruments and data of the two observation stations are the same, and all sampling rates of raw data are 10 Hz. The instrument used was a sonic anemometer (CSAT3, Campbell Co., USA) observing 3-D wind speed fluctuation and temperature fluctuation, open-path H_2O/CO_2 analyzer (LI-7500, LI-COR Co., USA) observing densities fluctuations of water vapor and CO_2. The height of eddy covariance measurement system were put on 2 m and 41 m in Yucheng and Changbai sites. In addition, some auxiliary observations were also carried on, such as air temperature and humidity (HMP45C, VAISALA Co., Finland), wind speed (A100R, Vector Ins., England) in various heights, soil and surface temperatures at five different depths (TCAV, CS-107, Campbell Co., USA), soil humidity in three different depths (TDR, CS615-L, Campbell Co., USA), net radiation (CNR1, KIPP & ZONEN, Holland) calculated by the measurements of 2 long-wave radiometers and 2 short-wave radiometers and 2 soil heat flux plates buried underground 2 cm.

3 Results and discussions

3.1 The influences of different averaging period on the estimates eddy covariance fluxes

In theory, the eddy covariance technique should satisfy the requirement that the mean vertical velocity during the averaging periods is equal to zero. But in most practical situations the mean vertical velocity is not zero due to many reasons. According to eq. (10), it is found that the arithmetic mean value of covariance calculated by multiple short averaging periods is unequal to the one calculated directly by a longer averaging period (total time is equal to the preceding one), and the averaging period may influence the flux results. Nowadays typical averaging period is 15—30 min in most micrometeorological researches. What we are interested in is what would take place if the averaging period is very short (e.g., 1 min) and very long (e.g., 2—6 h).

The diurnal change course of CO_2 fluxes and latent heat fluxes in the Yucheng station estimated by various averaging periods is illustrated in fig. 1, in which all the averaging periods are no more than 30 min, and the results of less than 30 min averaging period are converted arithmetically into 30 min. As shown in fig. 1, it is obvious that the shorter the averaging period is, the less the absolute value of fluxes will be. The distinctions between the fluxes calculated by different averaging periods are higher at midday than in the morning or at sunset.

Table 1 lists various regression equations and statistics. The fluxes of different averaging periods are used as independent variables and the fluxes estimated by 30 min as dependent variable in the Yucheng station. It is suggested that, compared with the fluxes of 1×30 min, the shorter the averaging period is, the less the calculated fluxes are, and the bigger the relative error and root mean squares difference is. In table 1, the fluxes distinction between 3×10 min and 1×30 min is only about 1%, while the flux distinction between 30×1 min and 1×30 min is about −12%. So 10 min can still be used as the averaging period over wheat field in the Yucheng station. In other words, there is almost no distinction between flux results when the averaging period changes from 10 to 30 min, which is about 1%.

Figure 2 shows that the mean values of F_c and $(H+LE)$ in the daytime in the Yucheng station vary with the averaging period for 4 d. When the averaging period changes from 1 to 30 min, the intensity of fluxes (absolute value) is obviously from lower to higher, then the intensity of the absolute value of fluxes becomes steady when the averaging period changes from 30 to 120 min, and when the averaging period becomes even longer, the fluxes overall become unstable and greater. So it is incorrect to estimate the fluxes over wheat field if the averaging period is longer than 120 min.

3.2 A normalized ratio to determine the range of averaging period parameters.

In order to determine the range of averaging period in eddy covariance measurements over various surface conditions, in this paper a simple me-

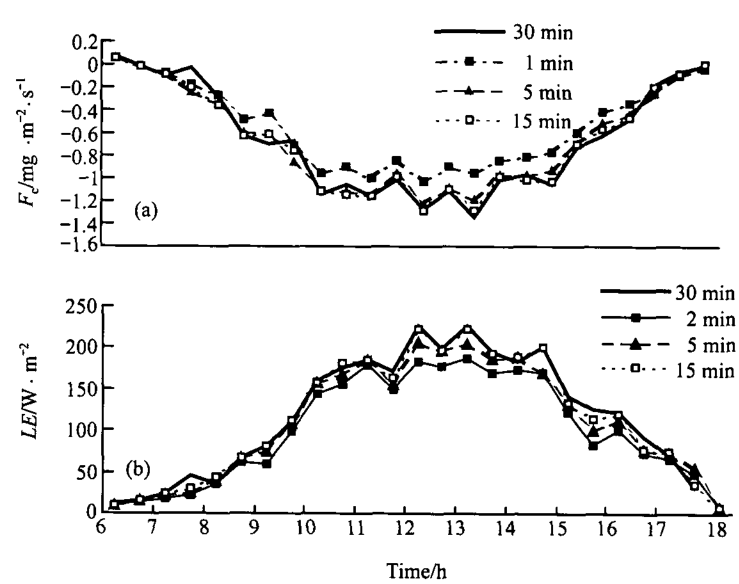

Fig. 1. The diurnal change of recalculated CO_2 flux (a) and latent heat flux (b) with different averaging periods (Yucheng station, May 4, 2003).

Table 1 Statistics of fluxes recomputed with different averaging periods (YC)

Fluxes	Averaging period/min	Regression equation	R^2	Mean	Relative bias(%)	Std
	30×1	$y = 0.878x-0.005$	0.9757	−0.678	−11.31	0.094
	15×2	$y = 0.929x-0.0066$	0.9858	−0.716	−6.29	0.068
	10×3	$y = 0.9451x-0.0104$	0.9874	−0.732	−4.18	0.061
F_c/mg • m^{-2} • s^{-1}	6×5	$y = 0.9648x-0.0126$	0.9911	−0.749	−1.93	0.050
	3×10	$y = 0.9814x-0.0133$	0.9917	−0.763	−0.18	0.047
	2×15	$y = 0.9921x-0.0041$	0.9937	−0.762	−0.31	0.040
	1×30	$y = x$	1	−0.764	0.00	0.000
	30×1	$y = 0.8816x-1.1856$	0.9666	114.5	−12.58	16.0
	15×2	$y = 0.9371x-1.7161$	0.9837	121.0	−7.64	10.8
	10×3	$y = 0.9533x-1.0254$	0.9859	123.8	−5.47	9.8
LE/W • m^{-2}	6×5	$y = 0.9742x-0.697$	0.9922	126.9	−3.13	7.1
	3×10	y = 0.9891+0.1534	0.9963	129.7	−0.98	4.8
	2×15	$y = 1.0035x-1.7588$	0.9963	129.7	−0.99	4.8
	1×30	$y = x$	1	131.0	0.00	0.0
	30×1	$y = 0.8661+0.0832$	0.9827	42.6	−13.41	9.1
	15×2	$y = 0.9255x-0.1003$	0.9893	45.4	−7.75	6.2
	10×3	$y = 0.9429x-0.0495$	0.9917	46.4	−5.69	5.3
H/W • m^{-2}	6×5	$y = 0.9736-0.1469$	0.9942	47.7	−3.00	4.1
	3×10	$y = 0.9883x+0.0629$	0.9944	48.7	−1.09	3.8
	2×15	$y = 0.9963x-0.1199$	0.9969	48.9	−0.66	2.9
	1×30	$y = x$	1	49.2	0.00	0.0

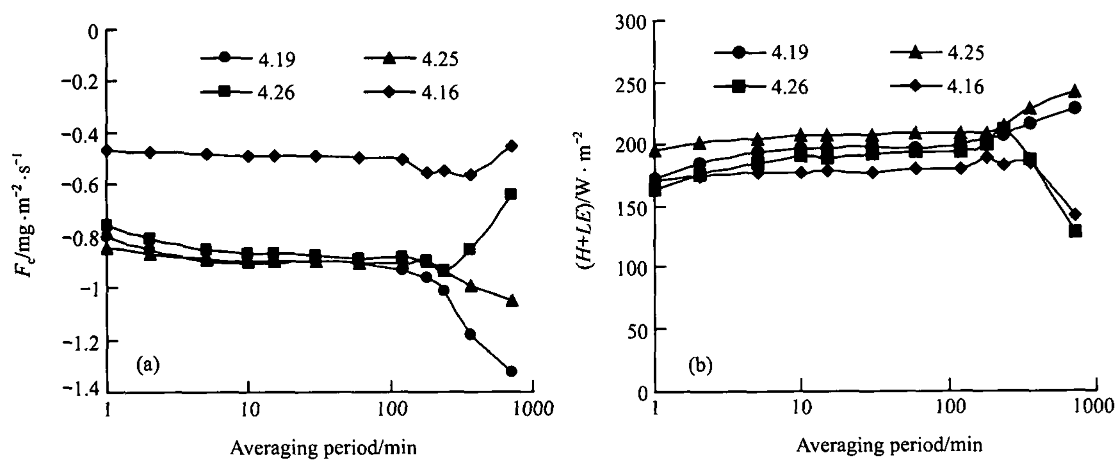

Fig. 2 Averages of F_c(a) and $(H+LE)$ (b) of daytime vary with the averaging period in 4 days (Yucheng station, May, 2003).

thod of normalized ratio is given, which is the ratio of fluxes calculated by various averaging periods to that calculated by criterion averaging period. By this method the range of averaging period can be determined when eddy covariance is used over various ecological surfaces with dynamic changes. Fig. 3 shows obviously the influences of different surface conditions and different averaging periods on flux estimates and its distinction, which indicates that the normalized ratio method is quite efficient, and more intuitionistic and understandable than fig. 1.

The geographic conditions of the Yucheng station and the Changbai Mountains station are quite distinct. In the Changbai Mountains station, the forest is mainly of broadleaf pine, where the land surface slope is no more than 4%, and the main arbor is Korean pine, lime tree, Mongolian oak, Manchurian ash, color wood, etc. There are double-layer structures and different age trees in the forest. The average height of the arbor is 26 m in the upper layer of the forest, and the density of tree is about 560 hm^{-2}. The bush cover degree in the lower layer of the forest is 0.4, which includes mainly honeysuckle, mountain plum. The herbaceous plant coverage degree is as high as 0.7, which includes mainly mountain eggplant, wide-leaf tongue grass and scouring rush, where the height of instruments is 41 m. Fig. 3 clearly shows that the fluxes in the forests vary with various averaging periods, and also indicates that the low-frequency component of the fluxes in forests has obvious distinction, so it is necessary to pay more attention to the attenuation and loss of low-frequency fluxes in the forests. Relative to the fluxes calculated by 30 min averaging period, when the averaging period changes between 10 and 60 min, the change of the calculation fluxes in the Changbai Mountains is smaller than 8%; when the averaging period changes within 10 min, the calculated fluxes trend to decrease obviously, and when taking 1 min as an averaging period, the calculated fluxes in the Changbai Mountains reduce by 52%, which is a remarkable contrast with the ones in the Yucheng station. In addition, the subject of this paper will be discussed by analyzing various spectra of the observations.

In figs. 2 and 3, what is worth noticing is when the averaging period is longer than 180 min. There are variations in both the fluxes calculated directly and the fluxes by normalized ratio in various degrees, which cannot be explained by authors at present. A possible reason for the variations is related to the atmospheric forming and weather conditions, because the too long averaging period will lead to the deviations of unspecific conditions of the layer near to the surface, in which cases it is meaningless to calculate fluxes.

4 Conclusions

The influence of averaging period on flux estimates is analyzed by using 10 Hz eddy covariance raw data observed over two different surface conditions. It is suggested that (i) because the vertical velocity is not equal to 0 during a specific interval or there is a trend of overall changes (low frequency change) of vertical wind speed and other scalar, in most conditions, different averaging periods would lead to different eddy covariance estimates of fluxes, especially when observing over the land surfaces with complex terrain and hypsography. (ii) By integrating all limitations in field observations, it is found that, 30 min averaging period is suitable for long-term observation and research, while 10 min for specific and detailed research, and as for long-term observation and research in the Changbai Mountains station, 30—60 min should be better. To calculate fluxes over two stations above, the averaging period should not be too long, when the averaging period is over 120 min, the calculated fluxes

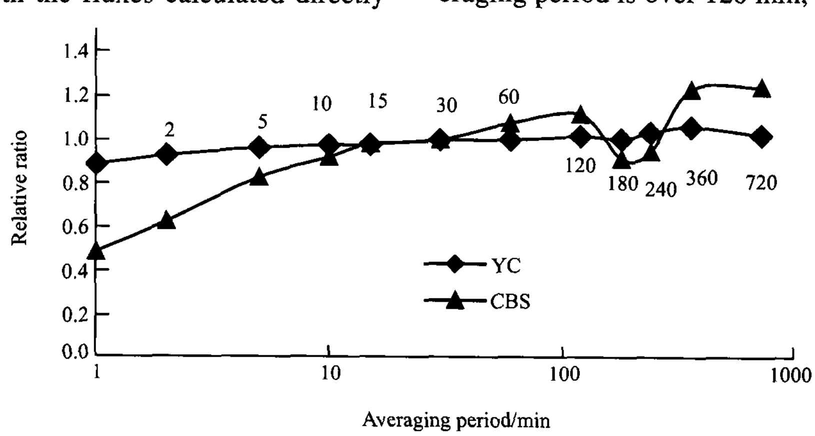

Fig. 3. The normalized ratio of $(H+LE)$ calculated by various averaging period with 30 min $(H+LE)$ in the Yucheng (YC, May, 2003) and Changbai Mountains stations (CBS, August, 2003).

would increase and become unsteady (the max relative error is over 20%). (iii) By analyzing the comparison of the measurements over farmlands and those over the surface of various types of forests, it is found that, with the increase of averaging period, the fluxes over forests with tall trees are more prone to increase than those over scrub farmlands. The result is basically the same with Finnigan's conclusion: "averaging period should be longer than the usual interval (for example 30 min), for example 2—4 h", drawn by analyzing measurements over forests. It shows that the surface conditions play a significant role in the determination of averaging period by the eddy covariance technique, to which should be paid more attention.

In this paper, primary conclusions are drawn only by analyzing the measurements in the Yucheng and Changbai Mountains stations. It is very necessary to analyze similar measurements in other experimental stations, especially the observation stations in forests with complex surface conditions. In practical situations, the eddy covariance technique is influenced simultaneously by roughness, atmospheric stability and surface wind speed, which are the key influencing factors of surface conditions. What is discussed in this paper is very complicated, and needs to be understood and solved theoretically by further work. Therefore, more attention should be paid to the influences of averaging period on eddy covariance estimates of fluxes. And flux calculation over complex surface conditions should be the focus in the future.

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