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Overview of ChinaFLUX and evaluation of its eddy covariance measurement

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Abstract

The Chinese Terrestrial Ecosystem Flux Research Network (ChinaFLUX) is a long-term national network of micrometeorological flux measurement sites that measure the net exchange of carbon dioxide, water vapor, and energy between the biosphere and atmosphere. The ChinaFLUX network includes 8 observation sites (10 ecosystem types) and encompasses a large range of latitudes (21°57′N to 44°30′N), altitudes, climates and species. It relies on the existing Chinese Ecosystem Research Network (CERN), fills an important regional gap and increases the number of ecosystem types in FLUXNET. Data and site information are available online at the ChinaFLUX web sites (http://www.chinaflux.org/). Expanding the scope of the FLUXNET database, ChinaFLUX offers new opportunities to quantify and compare the magnitudes and dynamics of annual ecosystem carbon and water balance and to explore the biotic and abiotic effects on ecosystem processes of carbon dioxide and water vapor exchange that are unique to ecosystems in China, such as the vegetation communities on the Qinghai–Tibet plateau. Besides, ChinaFLUX also provides more insights to help define the current status and enable future prediction of the global biogeochemical cycles of carbon, water and trace gases. Recent findings from the ChinaFLUX network are summarized in both micrometeorological and ecological aspects. This paper also summarizes these results and makes recommendations for the research priorities in ChinaFLUX.

Keywords: Eddy covariance; Complex terrain; Qinghai–Tibet plateau; Carbon and water cycle; Asian monsoon climate

1. Introduction

The increase in the atmospheric CO_2 concentration constitutes a critical change of the earth climate system. A proper understanding of the global carbon cycle is critical for predicting how this change will affect the future climate and its environmental impacts. Toward that end, a number of international networks have been established to monitor the carbon cycle in the terrestrial environment, including both ground networks of global scope and satellite-based observations. Among these is the global network (FLUXNET) of over 250 sites where tower-based eddy covariance methods provide continuous measurements of the land–atmosphere exchanges of CO_2, water vapor, heat and other entities (Valentini et al., 2000; Baldocchi et al., 2001).

The Eurasian continent is the largest in the world. To date, terrestrial ecosystem flux research in Eurasia has emphasized field campaigns in Siberia as part of the EUROSIBERIAN CARBONFLUX project (Schulze

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et al., 2002) or site-specific experimental studies (e.g. Kelliher et al., 1999; Hollinger et al., 1998). Few carbon dioxide flux studies based on eddy covariance technique have been conducted in China (e.g. Kato et al., 2004). The ChinaFLUX program, launched in 2002, fills an important regional gap in FLUXNET and increases the number of ecosystem types being represented by the long-term observations.

China is one of the largest countries in the Eurasian continent. Geographically, the northwestern part of China is located in the hinterland of the Eurasian continent, its southeastern part facing the Pacific, with the Qinghai–Tibet Plateau as the highest terrain of the earth in the southwest of China. Such sharp variations in topography are responsible for the intense monsoon climate along the eastern coast and continental climate in the interior. A large number of climate zones have been delineated as plateau, cold (sub-cold) temperate, temperate, warm temperate, subtropical, and tropical climate zones (e.g. Cheng, 1993; Wu, 1995). Driven by these complex terrain and climate features, a great variety of soil and vegetation types are found in China. In eastern China, forest types follow a clear latitudinal pattern, ranging from needle forest in the north to the deciduous broad-leaved forest, mixed needle and broad-leaved forest, evergreen broad-leaved forest, tropical seasonal rainforest, and tropical rainforest in the south. Along the southeast to northwest transect, the landscape changes from forest to grassland and arid desert. On the Qinghai–Tibet Plateau there exist subtropical and temperate alpine meadows, grassland and desert (e.g. Gu et al., 2000; Liu and Jiao, 2000). Indeed, almost all vegetation types distributed in the northern hemisphere can be found in China.

This paper provides an overview of ChinaFLUX. In Section 2, we discuss the design strategy of the network, including its scientific objectives, the considered rationale behind site selection and research methodology. Highlights of early results from the network, both micrometeorological and ecological, are summarized in Sections 3 and 4, respectively. In the final section (Section 5), we briefly discuss scientific challenges that the network faces and its future outlook. Synopses of the technical papers in this special issue are given to help the reader put the site-specific information in a broader context.

2. Network design strategy

2.1. Scientific objectives

ChinaFLUX is a long-term network that relies on the Chinese Ecosystem Research Network (CERN) and applies the eddy covariance technique and chambers as the main research methods to study CO_2, H_2O, and heat fluxes between vegetation and the atmosphere in typical Chinese ecosystems. ChinaFLUX has four main scientific objectives.

(1) To develop the standard methodology for long-term measurement of terrestrial ecosystem CO_2, H_2O and heat fluxes in China. The eddy covariance method, a core component of the FLUXNET methodology, is relatively new to Chinese scientists. At the outset of the network design, it is recognized that the expertise of the experts in countries where long-term flux observations were first launched must be relied upon. Close collaboration with colleagues in these countries ensures rapid technological transfer, and will likely avoid reinventing the wheel and identify critical needs to further improve the method.
(2) To obtain data on the net ecosystem exchanges of CO_2, H_2O and heat in a variety of vegetation communities, and data on CO_2, CH_4 and N_2O emission from and/or uptake by the soil in these communities. In addition to expanding the scope of the FLUXNET database, such datasets offer new opportunities for exploring biotic and abiotic influences on the exchange processes that are unique to ecosystems in China. For example, the vegetation communities on the Qinghai–Tibet Plateau must cope with low atmospheric CO_2 pressure and strong solar radiation (Fu et al., 2006), and those in the southeast are frequently subject to extreme heat stress (maximum daily temperature in excess of 40 °C) in the growing season (Wen et al., 2006). Because of the widespread human footprint (in the form of cropland and heavily managed forest plantation), the data will also provide insights on how management practices affect terrestrial carbon sequestration and fluxes of other greenhouse gases.
(3) To obtain data on those ecological patterns and processes those are relevant to carbon cycle in the terrestrial environment. Photosynthesis and respiration rates, biomass pool size, species, litterfall and soil organic matter content are among the ecological parameters being monitored. These ecological measurements provide independent validation of the eddy covariance estimates of the net ecosystem carbon exchange (Barford et al., 2001) and parameters for constraining Soil–Vegetation–Atmosphere Continuum (SVAC) models (e.g. Wang et al., 2005, 2006; Ren et al., 2005).
(4) To develop process-based models of water and carbon cycles for typical Chinese ecosystems.

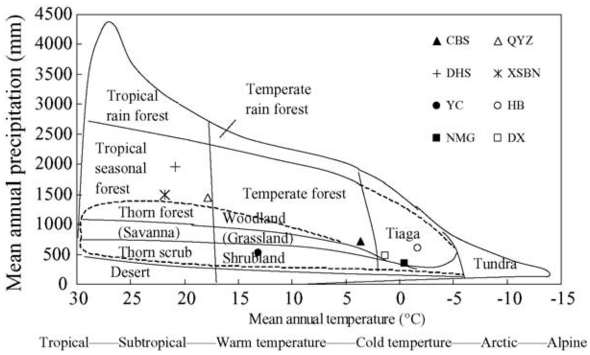

Fig. 1. ChinaFLUX sites in the climate space. Refer to Table 1 for site name abbreviations.

Development of models is a crucial component of the network program. Once validated against the observations, and with the aid of remote sensing, these models will allow us to relate in situ measurements to other ecosystem types, and provide information for the validation of net primary productivity, evaporation, and energy absorption that are being generated by remote sensing in regional and continental scales (Baldocchi et al., 2001; Yu et al., 2005b).

2.2. Site selection

Currently, ChinaFLUX consists of 8 sites (10 ecosystem types) that apply the micrometeorological method and 17 sites that use the chamber method. The micrometeorological sites were selected from the existing CERN sites to represent major ecosystem and climate types in China (Figs. 1 and 2, Table 1), all of which include both eddy covariance and chamber fluxes measurements but mainly focus on eddy covariance measurement of CO_2 and water vapor fluxes. The sites with only chamber measurements put greater emphasis on the CH_4 and N_2O fluxes (Dong et al., 1998; Zheng et al., 2003).

The three grassland sites (HB, NMG and DX), located in the northwestern part of China along the Temperate-Alpine Rangeland Transect (China Grassland Transect, CGT) (Fig. 2), which spans from the Daxinganling Mountain Range in the northeast to the Qinghai–Tibet Plateau in the southwest, cover an altitudinal range from 1200 to 4300 m (Table 1). The CGT transect is a part of the Euro-Asian Continental Grassland Transect (EACGT). The HB site includes three ecosystem types that represent the typical grassland vegetation on the Tibet Plateau in

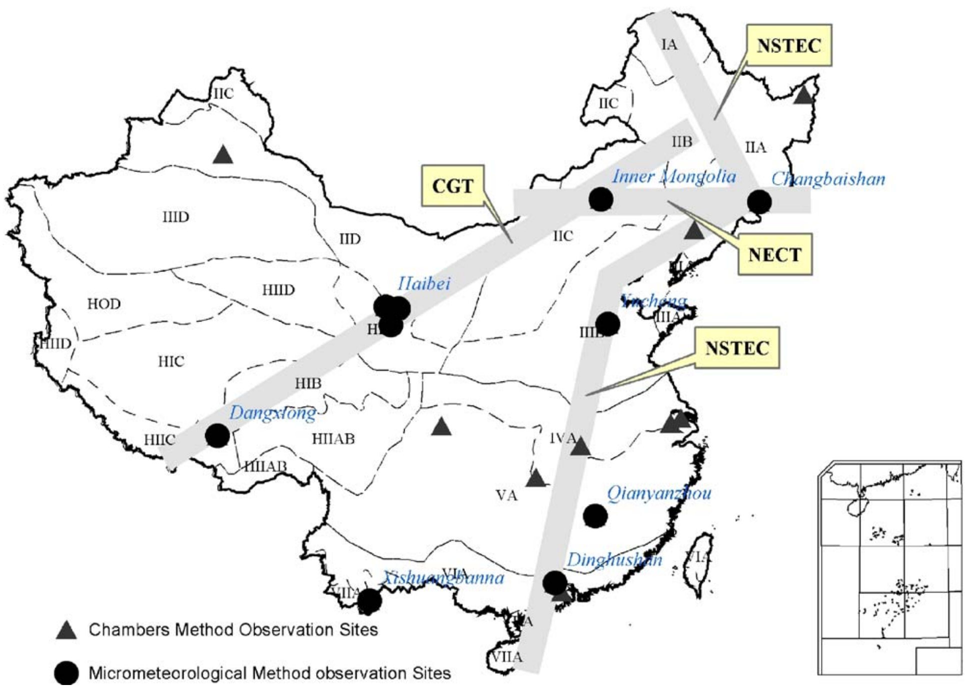

Fig. 2. The distribution of eddy flux (●) and chamber flux (▲) observation site of ChinaFLUX. The gray strip (▢) shows the extension of three terrestrial transects of China, which are the China Grassland Transect (GCT), the North–South Transect of Eastern China (NSTEC) and the North East Chinese Transect (NECT), respectively.

Table 1
General background of ChinaFLUX sites with the eddy covariance technique of micrometeorology as their main measurement methods

Sites (abbreviation)	Location and altitude	Climate and soil	Vegetation	Canopy height	Reference in this issue
Changbaishan forest site (CBS)	42°24′N 128°05′E; 738 m	Temperate continental monsoon climate Upland dark brown forest soil	Temperate deciduous broad-leaved and coniferous mixed forest *Pinus koraiensis*, *Tilia amurensis*, *Quercus mongolica*, *Fraxinus mandshurica*, *Acer mono* etc.	26 m	Guan et al. (2006), Zhang et al. (2006a), Zhang et al. (2006b) and Sun et al. (2006)
Qianyanzhou forest site (QYZ)	26°44″N 115°03′E 102 m	Typical subtropical monsoon climate Typical red earth	Typical subtropical monsoon man-planted forest *Pinus elliottii*, *Pinus massoniana*, *Cunninghamia lanceolata*, *Schima superba*, etc.	12 m	Wen et al. (2006), Zhang et al. (2006b) and Sun et al. (2006)
Dinghushan forest site (DHS)	23°10′N 112°34′E; 300 m	Monsoon humid climate of torrid zone of south Asia Lateritic red-earth, yellow-earth, and mountain shrubby-meadow soil	Typical subtropical typical tropical evergreen broad-leaved forest *Cleistocalyx operculatus*, *Syzygium jambos*, *Castanopsis chinensis*, *Pinus massoniania*, *Rhododendron moulmainense* etc.	20 m	Zhang et al. (2006b)
Xishuangbanna forest site (XSBN)	21°57′N 101°12′E; 756 m	Typical monsoon humid climate of torrid zone of south Asia Lateritic and red lateratic soil	Tropical seasonal rain forest *Pometia tomentosa*, *Terminalia myriocarpa*, *Barringtonia macrostachya*, *Gironniera subaequalis*, *Mitrephora maingayi*, *Garcinia cowal*, *Knema erratica*, *Ardisia tenera*, *Mezzettiopsis creaghii*, *Dichapetalum gelonioides*	40 m	
Yucheng cropland site (YC)	36°57′N 116°36′E; 28 m	Temperate semi-humid and monsoon climate Soil type is aquox and salt aquox, and surface soil is rich in light-mid loam	Warmer temperate dry farming cropland Winter wheat and summer maize	0.8 m (wheat); 3 m (maize)	Sun et al. (2006) and Wang et al. (2006)
Haibei grassland site (HB)	37°36′–37°39′N 101°18′–101°20′E; 3215–3360 m	Highland continental climate Soil type is alpine meadow soil, alpine scrubby meadow soil, and swamp soil	Typical frigid vegetation of Northern Qinghai–Tibetan Plateau *Potentilla fruticisa* shrub, *Kobresia humilis* meadow and *Kobresia tibetica* swamp meadow	0.6 m (shrub); 0.2 m (meadow); 0.5 m (swamp)	Fu et al. (2006)
Inner Mongolia grassland site (NMG)	44°30′N 117°10′E; 1189 m	Temperate semi-arid continental climate Chernozem soil	Typical steppe and meadow steppe *Leymus chinense*, *Stipa grandis* and *S. krylovii*. *Stipa Baicalensis*, *Festuca Lenesis*, *Filifolium sibiricum*	0.4 m	Fu et al. (2006)
Dangxiong grassland site (DX)	30°51′N 91 °05′E; 4250 m	Plateau monsoon climate Meadow soil with sandy loam	Typical *Kobresia* meadows of the northern Tibetan plateau *Kobresia littledalei*, *Blysmus sinocompressus*, *K. microglochin*	0.15 m	

China, where the influence of the monsoon climate is small.

The four forest sites (CBS, QYZ, DHS, and XSBN) are influenced by monsoon climate to varying degrees. CBS is an old-growth climax forest, in the temperate conifer-broadleaved forest zone, which was regenerated after a natural fire about 450 years ago (Guan et al., 2006). Because human disturbance to CBS is minimal, carbon uptake by this forest can serve a benchmark for understanding the impact of forest management on carbon sequestration. QYZ is a plantation forest, which was planted in 1985 on the transitional zone from subtropical evergreen forest to the temperate forest. One important consideration for including QYZ in the network is that plantation forests represent a significant portion of all the forested land in China and are thought to be a major component of the national carbon budget (Zhang et al., 2000; Fang et al., 2001). The other two sites (DHS and XSBN) are in well-protected natural forests on the subtropical zone in southern China. They expand the network coverage in the climate space (Fig. 1).

The DHS, QYZ, and CBS forest sites are distributed along the North–South Transect of Eastern China (NSTEC, the Fifteen Transect of Global Change and Terrestrial Ecosystems, GCTE) (Fig. 2). The NSTEC transect is part of the Euro-Asian Continental Eastern Transect (EACET), while the NMG and CBS sites are along the North East Chinese Transect (NECT, the Fifth Transect of GCTE). Along the NECT transect, the landscape changes from forest to grassland, and the NECT transect becomes a bridge between the forest transect of NSTEC and the grassland transect of CGT (Fig. 2).

A crop site (YC) in the Northern China Plains, where annual rotation of wheat and maize is the dominant farming practice, was also equipped with the eddy covariance instrumentation. Although the net, long-term carbon flux in croplands, particularly heavily tilled ones as YC, is negligibly small (Robertson et al., 2000), the eddy covariance and ecophysiological measurements provide us useful data for SVAC model development and validation (Yu et al., 2001; Wang et al., 2006). Additionally, the data will be used to investigate crop water use which is an important water conservation issue (Liu et al., 2002).

All the above sites and transects are critical in regulating global climate change on the Euroasia continent. The selection of these micrometeorological sites is a trade-off between micrometeorological criteria and the above-mentioned ecological considerations. While the grassland and crop sites are flat, the complexity of the terrain varies among the four forest sites: CBS is flat; QYZ is on gently undulating terrain, DHS is on a 30° slope, and XSBN is in a small valley (for 3D topography of these sites, see http://www.chinaflux.org/). Clearly, given the advective influences on the eddy fluxes over complex terrain (Lee, 1998; Baldocchi et al., 2000; Lee and Hu, 2002; Aubinet et al., 2003), eddy covariance measurement made over the topographically complex sites (DHS and XSBN) have value, even though the annual estimates of net ecosystem production (NEP) may be error prone. Flux measurement over non-ideal sites can provide information on the relationship between carbon fluxes and phenology, quantify how ecosystem-scale carbon fluxes respond to environmental perturbations, and determine the factors causing interannual variability in carbon fluxes (Baldocchi, 2003).

2.3. Research methods

2.3.1. Micrometeorological measurement

The micrometeorological measurement protocol (hardware, software, data format) is standardized across all ChinaFLUX sites. Eddy fluxes are measured with eddy covariance systems consisting of an open-path CO_2/H_2O gas analyzer (model LI-7500, Licor Inc., Lincoln, Nebraska) and a 3-D sonic anemometer/thermometer (model CSAT3, Campbell Scientific Inc., Logan, Utah). A data logger (model CR5000, Campbell Scientific Inc., Logan, Utah) records the eddy covariance signals at 10 Hz for archiving and on-line computation of the turbulence statistics. All fluxes were computed by block averaging over 30 min. Corrections were made for the effects of fluctuations in air density on the fluxes of CO_2 and water vapor by the online flux computation and post-field data processing programs (Webb et al., 1980; Leuning, 2004). Calibration of the analyzer is done every 6 months against a dewpoint generator for water vapor and a standard gas for CO_2. Span values of two consecutive calibrations usually differ by less than 3%.

ChinaFLUX has acquired several spare open-path eddy covariance systems for focused field campaigns. For example, in 2002–2004, a total of three identical systems were operated at the QYZ forest, at heights of 39.6 (permanent height), 31.6, 23.6 (permanent height), and 15.6 m above the ground. The flux profile data will be used to investigate methodological issues such as footprint, advection, flux divergence, and tower aerodynamic interference. At the HB grassland site, there are three identical eddy flux measurements over three different vegetation types within 10 km^2 under identical climate conditions on the Qinghai–Tibet Plateau, one of those operated by a Japanese group (Kato et al., 2004).

The open-path system has the advantage of being relatively easy to maintain. This is important in view of the fact that some of the sites are in remote locations. But we also recognize that closed-path eddy covariance systems are more commonly used in Europe and the USA. To ensure data comparability with other FLUXNET sites and to evaluate the performance of the open-path system, we have installed a closed-path system in parallel with the open-path system at two forest sites (CBS and QYZ). The system was custom-designed by Campbell Scientific, Inc.

The eddy covariance measurements are supplemented with a 6-level CO_2/H_2O and a 7-level CO_2 profile system, also custom-designed by Campbell Scientific Inc., at the crop/grassland sites and the forest sites, respectively. Standard meteorological measurements include air humidity, wind speed and direction, four components of the net radiation, photosynthetically active radiation, soil heat flux, soil temperature, and soil moisture.

The 30-min eddy flux data, 10 Hz raw data and other auxiliary data are sent to a central ChinaFLUX data office for archiving and processing (Fig. 3). Eddy fluxes are re-computed from the raw time series and are merged with the online flux data when the raw time series are lost due to system failure. The data are subject to a series of data quality control steps following Aubinet et al. (2000), Foken et al. (2004) and others.

2.3.2. Ecological measurement

Ongoing research at the eddy flux sites by the CERN scientists has produced data on most of the stand

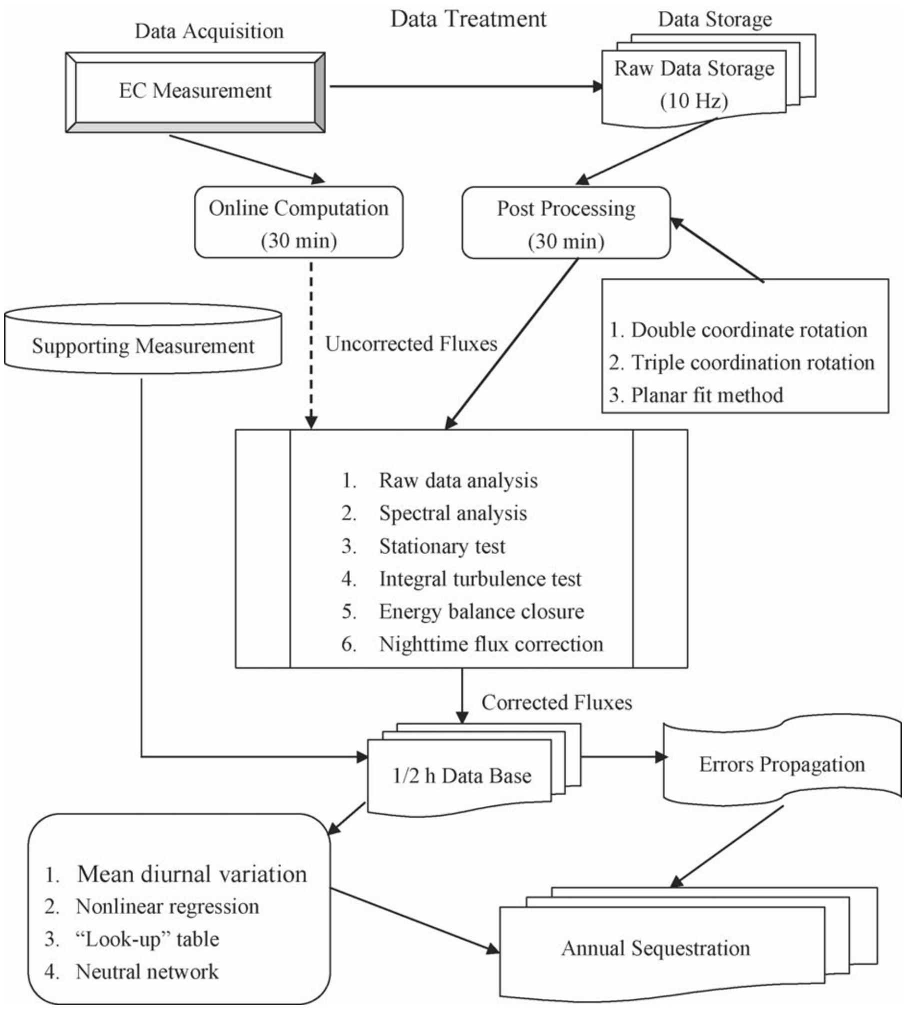

Fig. 3. Flow chart of data acquisition, processing and archiving. Dash line indicates that the online flux data will be used if the raw time series lost due to system failure.

variables recommended by the AmeriFlux Science Plan for vegetation, litter and soils (http://public.ornl.gov/ameriflux). In addition, process measurements are conducted on leaf gas exchange parameters, leaf area seasonal variations and soil respiration flux.

Soil respiration measurements are made with a static chamber-gas chromatographic technique developed by the Institute of Atmospheric Physics of the Chinese Academy of Sciences (Wang et al., 2003) at both the eddy flux sites and the chamber-only sites (Fig. 2). Measurement frequency is twice per week (9:00–11:00 at local time) and is supplemented with a measurement of diurnal variations every month. Air samples drawn by syringes are analyzed by gas chromatography for their CO_2, CH_4, and N_2O concentrations, providing simultaneous detection of fluxes of these gases. The ability to measure the three major greenhouse gases is particularly important for managed ecosystems where management practices may affect their fluxes differently (e.g. Robertson et al., 2000).

3. Eddy covariance data quality

For logistical reasons, ChinaFLUX has adopted the open-path instead of closed-path eddy covariance system as the standard flux measurement technique. To evaluate its performance, we have compared its measurement against a closed-path eddy covariance system at two forest sites (QYZ and CBS). Fig. 4 shows an example of such comparison at the QYZ site. In the early phase of the experiment, the two units were completely independent of each other, each having its own sonic anemometer and data logger. They were mounted at the same height and were 4 m apart laterally. In September 2003, we merged the two units by: (a) positioning the intake of the closed-path analyzer next to the open-path analyzer, (b) using the signals from the same sonic anemometer to do both the closed-path and open-path flux computations and (c) logging all signals with one single data-logger. A systematic bias was observed in the daytime flux prior to the modification, which we suggest was caused by the tower having different aerodynamic influences on the sonic anemometers. This bias was eliminated after the merging. The generally good agreement, along with the fact that span calibration of the open-path analyzer is very stable in time, indicates that the open-path approach is a good choice for the network (e.g. Song et al., 2005).

Concerns have been expressed on flux biases associated with finite sampling frequency and averaging length. Typically, high frequency flux loss is more serious in the surface layer over short vegetation

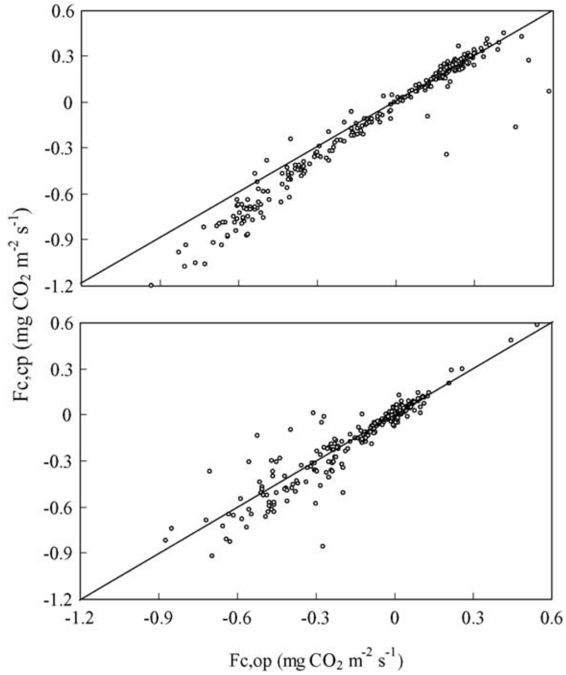

Fig. 4. Comparison of the CO_2 flux measured by the open-path ($F_{c,op}$) and closed-path eddy covariance system ($F_{c,cp}$) (a) before (22–28 June, 2003) and (b) after (20–26 October, 2003) system enhancement at QYZ forest site.

(grassland, crops) than over forests (Massman and Clement, 2004), whereas low frequency contributions associated with mesoscale motion appear to be more severe for forests (Malhi et al., 2004; Moncrieff et al., 2004). To address the effects of low frequency contributions on the fluxes measurements, Sun et al. (2006) applied the ‘ensemble block’ time average procedure and the Ogive function to determine the low frequency contribution to eddy fluxes at the YC (wheat), CBS and QYZ sites. Sun et al. (2006) concluded that the 30 min flux averaging periods are sufficient to capture all flux scales over a wheat field for the YC site, but 60 min or longer is necessary over tall forests of CBS and QYZ sites at the cost of losing information on processes at shorter time scales. At the forest sites, the flux estimations decrease rapidly if the averaging period is <30 min and increase smoothly if it >30 and <120 min. However, the estimation at all sites becomes unstable if it is >180 min. Their results show that the optimal averaging period is a site-specific parameter. Similar findings are reported by Finnigan et al. (2003) and Sakai et al. (2001). The procedure established by Sun et al. (2006) will be applied to other ChinaFLUX sites to determine the optimal averaging length.

Li et al. (2005) provided a summary of energy balance closure information for all the sites in 2003

Table 2
Summary of energy balance closure information, with the slope of a linear regression, S_1, and the slope of a linear regression forced through the origin, S_2, of the sum of eddy fluxes of sensible and latent heat against available energy

Site	S_1/S_2	Intercept	R_1^2/R_2^2	EBR
CBS	0.71/0.73	10.8	0.89/0.89	0.83
QYZ	0.72/0.76	16.9	0.88/0.88	0.77
DHS	0.70/0.74	24.4	0.77/0.76	0.82
XSBN	0.49/0.54	22.5	0.52/0.51	0.58
HB	0.70/0.77	40.4	0.93/0.90	0.91
NMG	0.70/0.73	13.7	0.94/0.93	0.83
DX	0.53/0.70	79.8	0.75/0.52	0.90
YC	0.81/0.88	23.2	0.89/0.78	1.00

R_1^2 and R_2^2 are coefficient of determination. EBR is energy balance ratio.

(Table 2). 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 derived from the ordinary least squares relationship between the half-hourly estimates of the independent flux variables ($H + \lambda E$) against the independent derived available energy (R_n–S–G), where H and λE are sensible and latent heat fluxes, respectively, R_n is net radiation flux, S is air heat storage, and G is heat flux into the soil (measured at 5-cm depth). Here, all flux variables are online computation (Fig. 3) and have not been corrected for high frequency losses (see Moore, 1986; Aubinet et al., 2000). Not considered in the calculation is heat storage in the top 5 cm soil layer and the aboveground biomass which would improve the closure by a few percentage points in the daytime and more at night. An extremely low energy balance closure found for XSBN was mostly likely caused by terrain complexity which is further discussed below. The degree of energy balance closure reported here, although comparable to that of Twine et al. (2000), falls in the lower range of the closure values reported in the literature (e.g. Wilson et al., 2002). Note that, excluding nonstationary cases substantially improves the surface energy balance (Mahrt, 1998), which was also not considered here. According to above-mentioned analysis (Sun et al., 2006), for some ChinaFLUX sites at least, an averaging period that captures the low frequency transport may improve the energy balance problem, although Malhi et al. (2004) pointed out that a longer averaging length does not always improve energy balance closure.

To obtain some appreciation of the terrain influence on the eddy covariance measurement, in Fig. 5 we plot a 1-week time series of CO_2 flux from the four forest sites. The plot is arranged according to terrain complexity, with the flat site (CBS) in the top panel and the most complex site (XSBN) in the bottom panel. At the flat CBS site, the diurnal pattern is very clean, showing little evidence of drainage flow at night. At QYZ on gently undulating terrain and DHS on a steep 30° slope, the nighttime flux is often negligibly small, a characteristic seen at many other FLUXNET sites, and is thought to result from drainage flow below the eddy covariance instrument (Lee, 1998). In part because of cold air drainage, the XSBN forest (in the bottom of a valley in mountainous terrain) is frequently inundated by fog, which usually forms around 10 p.m. and persists till noon on the next day. Fog droplets severely interfere with the gas analyzer and the sonic anemometer, causing a great many data spikes. Fig. 5 supports the contention that overall eddy flux data quality degrades as terrain complexity increases.

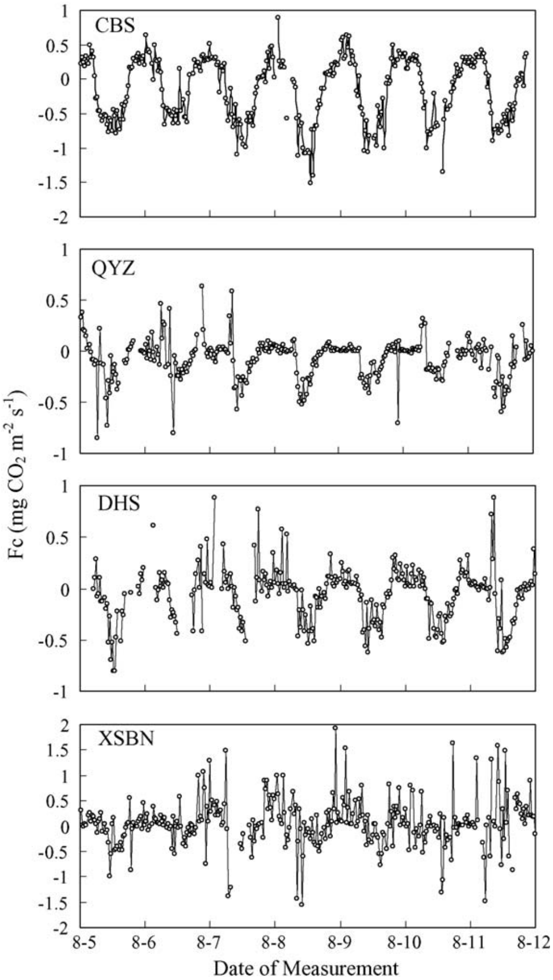

Fig. 5. A 1-week time series (5–11 August, 2003) of CO_2 flux at the four forest sites.

The above visual inspection of the terrain effect is supported by the examination of the friction velocity threshold for nighttime data (Goulden et al., 1996a). As shown by Guan et al. (2006), the nighttime CO_2 flux at the flat CBS site is not sensitive to friction velocity. Screening the nighttime data with a threshold of $u_* = 0.2$ m s^{-1} changes the estimate of the annual net ecosystem uptake by only 24.6 g C m^{-2} per year or about 13.5%. In comparison, at QYZ a threshold of 0.2–0.3 m s^{-1} is clearly evident in the CO_2 flux observed at two measurement heights (23.6 and 39.6 m; Wen et al., 2005). Encouragingly, the same threshold is also revealed by the integral turbulence characteristics of vertical wind velocity (Foken et al., 2004). Furthermore, the annual ecosystem respiration flux after implementing the friction velocity screening agreed to within 96.8–103.9% of that estimated from the dark respiration parameter of a model of the flux-light response (Wen et al., 2006). At the XSBN site, no clear friction velocity threshold can be established. The lack of a threshold has also been reported for other complex sites (Aubinet et al., 2000; Lee and Hu, 2002). Enhanced ecological measurements such as various components of the respiration flux, a task to be implemented by ChinaFLUX scientists in the near future, are crucial for the sites on complex topography in order to obtain credible estimates of the annual carbon sequestration.

In comparison to the nighttime observations, the daytime data quality is less adversely affected by terrain roughness. For example, using the daytime data from CBS, QYZ and DHS, Zhang et al. (2006b) discerned the dominant environmental factors that control the ecosystem light use efficiency and maximum photosynthetic capacity during the whole year. Similar conclusions are drawn by Baldocchi et al. (2000), Lee and Hu (2002) and others.

4. Biotic and abiotic controls on vegetation-air exchange

Zhang et al. (2006a) presented the first analysis of eddy flux over one full annual cycle within the ChinaFLUX network. They showed that despite its old age, the CBS forest is still sequestering carbon, adding to a growing body of evidence that old growth forests are not carbon neutral (e.g. Law et al., 2000; Knohl et al., 2003). The annual net ecosystem production (–308 ± 116 g C m^{-2} per year, Zhang et al., 2006a) is comparable with reported by those studies cited above (266–494 g C m^{-2} per year). However, Guan et al. (2006) also pointed that the annual ecosystem production was −182.3 g C m^{-2} per year at the same period and site. Their large discrepancy of the annual ecosystem production resulted from the different u_* threshold adopted (18.3% of their difference), and the different strategy of winter flux calculation (64.2%) (see detail in Guan et al., 2006; Zhang et al., 2006a). Their results showed that there are many uncertainties for determination of absolute values of long-term net carbon exchange even in sites with ideal topography using eddy covariance method (Massman and Lee, 2002; Baldocchi, 2003).

Another interesting and somewhat surprising result is that the forest appears to be able to photosynthesize around noon even in deep winter in freezing temperatures, one of reasons for their difference of annual ecosystem production mentioned above (Zhang et al., 2006a). For example, in December with mean air temperature of −9.8 °C and 5-cm soil temperature of −0.65 °C, the forest showed a small net uptake of −0.02 mg m^{-2} s^{-1} near noon. Others have observed carbon uptake by evergreen trees in winter months but not in freezing temperature (e.g. Hollinger et al., 1999). It is doubtful that this is statistically or physiologically significant, and the exact mechanism remains unclear at this time and will be pursued in future research. Without some understanding and ability to compensate for these differences, for example the winter flux, cross-site comparisons and national or global scale synthesis are difficult and uncertain at best.

Considerable debate has been focused on the role of plant and soil respiration in determining the carbon balance of forest ecosystems and how they will respond to future climate change (see Valentini et al., 2000; Giardina and Ryan, 2000; Grace and Rayment, 2000). How environmental conditions control ecosystem and soil respiration is a subject of numerous studies (e.g. Yu et al., 2005a). Of special interest is the confounding influences of temperature and soil moisture, which have been investigated in temperate climates (e.g. Davidson et al., 1998), Mediterranean climate (e.g. Xu and Qi, 2001; Reichstein et al., 2002), and in tropical seasonal forest (e.g. Davidson et al., 2000). Wen et al. (2006) contributes to this line of research by presenting an analysis of the whole-ecosystem respiration (as measured by eddy covariance) in a monsoon climate. Taking advantage of a drought coinciding with a record breaking hot spell that prevailed in southeastern China during the summer of 2003 (Waple and Lawrimore, 2003), they showed that a quadratic function best describes the dependence of the respiration quotient on soil moisture. Their study suggests that summer droughts and heat waves are two aspects of weather that likely play an important part in the annual NEP of forests in this region.

Respiration by soil autotrophs and heterotrophs can account for up to 75% of ecosystem respiration (Goulden et al., 1996b; Law et al., 2001). There is great spatial variability in soil respiration, accounting for 48% of the whole ecosystem respiration on average at the CBS site, without including the respiration of fallen trees and coarse wood debris (Guan et al., 2006). However, soil respiration could only account for about 39.4% of whole ecosystem respiration at the QYZ site, while only account for 26.6% without including the litter in 2003 (Liu, personal communication). The discrepancy mentioned above might result from differences in vegetation cover, site productivity, soil acidity and texture, quality and quantity of soil organic matter, and, of course, drought stress. Yu et al. (2005a) also pointed that air temperature should be the best variable of predicting the ecosystem respiration at the QYZ site, and soil temperature at CBS site. In addition, Shi et al. (2006) also presented total annual loss of 579 ± 13 g C m^{-2} per year from soil respiration at the Lhasa river valley on the Tibetan plateau. Their study suggests that soil temperature is the dominant environmental factor controlling temporal variation of soil CO_2 efflux, and that crop phenology modified the temperature dependence of soil CO_2 efflux in different growing periods.

The centralized data management enables timely cross-site synthesis. In a comparative study, Fu et al. (2006) examined soil moisture and heat stresses affected the net ecosystem flux of CO_2 in a humid alpine shrub (HB) and a semi-arid steppe (NMG). They found that midday down-regulation of NEE was much more pronounced at the dry steppe site than at the more moist shrub site. Furthermore, the optimal temperature for net carbon uptake of the alpine shrub was surprisingly low (10 °C) whereas that of the steppe vegetation did not show heat stress until temperature exceeded 20 °C, highlighting different impacts of future global warming on these two ecosystems. In another comparative study, Zhang et al. (2006b) investigated seasonal variations in ecosystem quantum yield and maximum photosynthetic capacity in three network forest sites (CBS, QYZ, and DHS). The hot and dry weather associated with the subtropical, synoptic pressure system caused the ecosystem photosynthetic capacity to decline at the two subtropical forests (QYZ and DHZ) in mid-summer, but not at the temperate forest (CBS).

Fig. 6 presents the results of another cross-site synthesis where the relationship between net ecosystem CO_2 exchange and photosynthetically active radiation was examined using the Michaelis–Menten equation for late spring 2003 (25 April to 1 May, Fig. 6a) and mid summer (5–11 August, Fig. 6b). In late spring, the photosynthetic capacity decreased across the functional types in the order: wheat (YC) > subtropical forests (QYZ and DHS) > tropical forest (XSBN) (Other sites were still dormant, see for example, Guan et al., 2006). In midsummer, the order appeared as maize (YC) > tempetemperate forest (CBS) > tropical forest (XSBN), subtropical forests (QYZ and DHS) and alpine shrub (HB) > semiarid steppe (NMG) and meadow (DX). In our view, comparative studies of this kind yield insights into the vegetation–atmosphere interactions that cannot be gained by site-specific investigations and thus enhance the value of the network.

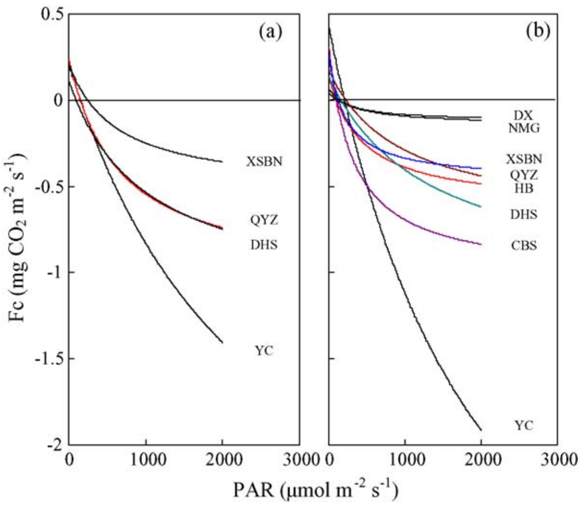

Fig. 6. The relationship between net ecosystem CO_2 exchange and photosynthetically active radiation was examined using the Michaelis–Menten equation for two periods in 2003 (25 April to 1 May (a); 5–11 August (b)).

5. Future outlook

The eddy covariance measurement technique has been widely used in the world, and such research has recently commenced in China. There are still many technical issues that need to be addressed. For example, advective effects are a major source of uncertainty on the eddy fluxes, particularly during the nighttime over complex terrain, and they may not be fully quantified without the aid of 2D and 3D models. However, drainage flows are likely to be amenable to observational studies and more studies of CO_2 drainage should be performed at the topographically complex sites (e.g. DHS and XSBN). To insure further progress on these nighttime flux issues and other related issues more research is needed into how gravity waves, intermittency, drainage, and pressure pumping affect flux measurements (Massman and Lee, 2002). Taking into account of moist sites (e.g. QYZ), the closed-path eddy covariance with a water resistant anemometer will be emphasized and developed.

Long-term measurement of the net exchange of CO_2, H_2O and energy fluxes between vegetation and the atmosphere have great potential to exhibit the role of Chinese terrestrial ecosystem in the global carbon and water cycles and improve our understanding of its environmental driving mechanism based on the ChinaFLUX sites along three major terrestrial transects in China (CGT, NSTEC and NECT in Fig. 2). The core objective of flux measurements is to explore the key processes and ecophysiological mechanisms in ecosystem carbon and water cycles and energy balance based on the synthetic inter-site comparison along the different transects. For example, the depression of net ecosystem CO_2 exchange under different stress conditions at DX, HB, and NMG sites (e.g. Fu et al., 2006), the separation of net CO_2 exchange into photosynthetic and soil respiration components etc., and the separation of evapotranspiration into plant transpiration and soil evaporation. Furthermore, it is necessary to understand the coupling mechanism of carbon and water cycles based on stomatal behavior for evaluating the carbon budget in Chinese ecosystems. Water use efficiency, an important integrated parameter in evaluating the terrestrial ecosystem carbon and water cycle, has high spatio-temporal variability at leaf and ecosystem levels (e.g. Yu et al., 2004), and there is great interest in understanding the factors controlling water use efficiency at different scales.

Eddy flux measurement itself cannot address the above issues. To understand the processes and mechanisms of ecosystem carbon and water cycle and energy balance, to evaluate and improve existing models, it will be necessary to combine dynamic eddy flux measurement with stable isotope technique and integrated ecosystem processes observations in forests, grasslands, and crops.

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