Advances in carbon flux observation and research in Asia

YU Guirui[1], ZHANG Leiming[1,2], SUN Xiaomin[1], FU Yuling[1,2] & LI Zhengquan[1,2]

1. Synthesis Center of Chinese Ecosystem Research Network (CERN), Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
2. Graduate School of the Chinese Academy of Sciences, Beijing 100039, China

Correspondence should be addressed to Yu Guirui (email: yugr@igsnrr.ac.cn)

Received July 14, 2004; revised January 21, 2005

Abstract As an important component of FLUXNET, Asia is increasingly becoming the hotspot in global carbon research for its vast territory, complex climate type and vegetation diversity. The present three regional flux observation networks in Asia (i.e. AsiaFlux, KoFlux and ChinaFLUX) have 54 flux observation sites altogether, covering tropic rainforest, evergreen broad-leaved forest, broad-leaved and coniferous mixed forest, shrubland, grassland, alpine meadow and cropland ecosystems with a latitudinal distribution from 2°N to 63°N. Long-term and continuous fluxes of carbon dioxide, water vapor and energy between the biosphere and atmosphere are mainly measured with eddy covariance technique to (1) quantify and compare the carbon, water and energy budgets across diverse ecosystems; (2) quantify the environmental and biotic controlling mechanism on ecosystem carbon, water and energy fluxes; (3) validate the soil-vegetation-atmosphere model; and (4) serve the integrated study of terrestrial ecosystem carbon and water cycle. Over the last decades, great advancements have been made in the theory and technology of flux measurement, ecosystem flux patterns, simulation and scale conversion by Asian flux community. The establishment of ChinaFLUX has greatly filled the gap of flux observation and research in Eurasia. To further promote the flux measurement and research, accelerate data sharing and improve the data quality, it is necessary to present a methodological system of flux estimation and evaluation over complex terrain and to develop the integrated research that combines the flux measurement, stable isotope measurement, remote sensing observation and GIS technique. It also requires the establishment of the Joint Committee of Asian Flux Network in the Asia-Pacific region in order to promote the cooperation and communication of ideas and data by supporting project scientists, workshops and visiting scientists.

Keywords: terrestrial ecosystem, flux observation and research, carbon flux, eddy covariance, Asia.

DOI: 10.1360/05zd0001

The continuously increasing concentrations of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) that mainly resulted from human activities, have greatly influenced the natural process and inherent carbon balance of terrestrial ecosystem and resulted in distinct global environmental changes that have challenged the sustainable development of human[1]. These issues have interested scientists from geography, ecology and environmental science to investigate the environmental controlling mechanism on carbon cycle in earth ecosystem, to evaluate the capability of carbon sequestration and illustrate its spatio-temporal patterns of carbon sink/source in terrestrial ecosystems, and to predict the response and adaptability of ecosystem carbon cycle to global change[1−3]. Such issues have also formed the essential contents of many global research projects as IGBP, WCRP and IHDP[1] that have greatly promoted global carbon research with the initiation of 'Global Carbon Project (GCP)' in 2003[4].

The long-term and continuous measurements of CO_2, H_2O and energy exchange between biosphere and atmosphere are necessary for understanding the key processes of global carbon cycling. The global flux network (FLUXNET, http://www.daac.ornl.gov/fluxnet) has a primary function for obtaining the information of CO_2, H_2O and energy fluxes in terrestrial ecosystems, providing basic data for analyzing the interaction among geosphere, biosphere and atmosphere and evaluating the function of terrestrial ecosystem in global carbon cycle[5]. At present, FLUXNET mainly consists of 7 regional networks, i.e. AmeriFlux (America), CarboEurope (Europe), OzFlux (Australia and New Zealand), Fluxnet-Canada (Canada), AsiaFlux (Japan), KoFlux (Korea) and ChinaFLUX (China), with 266 registered sites (up to Oct 2004). The multi-disciplinary, multi-scale research approaches have been employed in these flux networks to monitor the basic elements in soil-vegetation-atmosphere continuum and the key processes of carbon and water cycles in terrestrial ecosystems, which provided valid datasets and experimental platform for integrated research on ecosystem carbon cycle[5].

As the largest continent, Asia is typical of its vast territory, complicated topography, various climates type and abundant ecosystem diversity. The great differences in the economic status among the different regions within Asia also provide advantageous economic and social backgrounds for evaluating the impacts of human activities and social development on environmental changes. With AsiaFlux and KoFlux established in 1999 and 2000 respectively, the establishment of the Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFLUX) in 2003 has, to a certain extent, filled the regional gap of flux observation and research in Eurasia. At present, over 54 flux observation sites belonging to the three regional networks in Asia (i.e. AsiaFlux, KoFlux and ChinaFLUX) are operating on a long-term and continuous basis. The vegetation under study includes tropic rainforest, evergreen broad-leaved forest, broad-leaved and coniferous mixed forest, shrubland, and grassland and farmland, with a latitudinal distribution from 2° N to 63° N. However, the existing sites are not well distributed in different regions and ecosystems, with half sites located in temperate zone and most focusing on forest ecosystems. Besides, observation site in farmland ecosystems also mostly centered on paddy field. And it is of great significance to improve the spatial representativeness of flux observation site for accurately evaluating the spatial patterns of carbon sink/source in Asian terrestrial ecosystems. There has been great improvement in flux observation in China in recent years, with the establishment of ChinaFLUX and more flux sites installed under the support of Chinese Academy of Forestry and National Weather Bureau of China (personal communication), which will greatly promote the flux observation and research in Asia. The combination of large-scale environmental monitoring project, remote sensing and flux observation will also enhance the integrated research on flux observation and promote the comprehensive regional carbon budget (fig. 1).

Up to now, not only a mass of valid data have been obtained and accumulated, but also great advances in theory, methodology and instruments improvements have been achieved across regional flux networks in Asia, which contribute greatly to the global flux observation and carbon research. This study mainly reviewed the progress in instruments and methodology for flux observation and carbon research, the characteristics of CO_2, H_2O and energy exchanges in typical terrestrial ecosystems, the mechanism of environmental controls on fluxes and the modeling of ecosystem carbon cycle. We also presented the key scientific issues in flux observation and new regional cooperation in Asia and introduced the developments of ChinaFLUX.

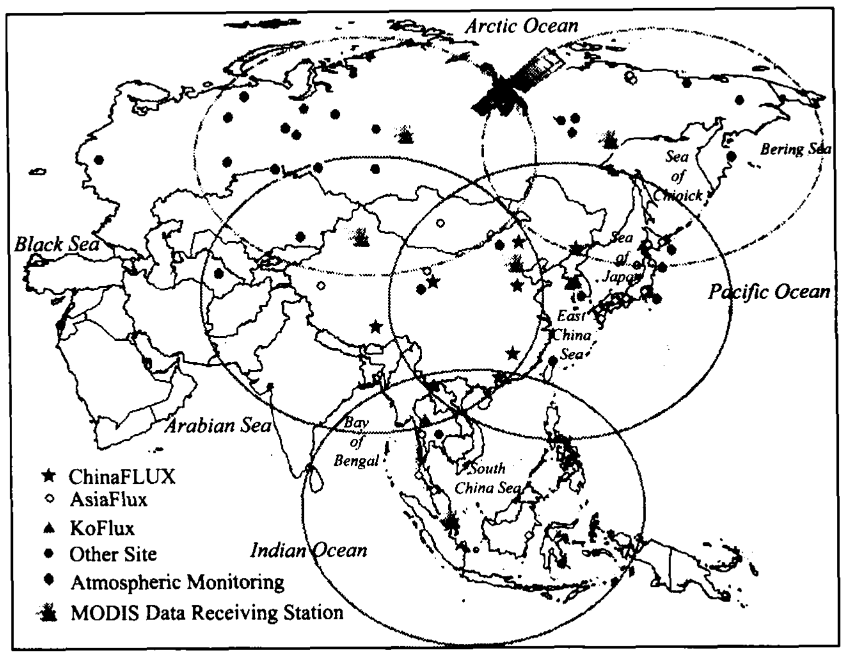

Fig. 1. The infrastructure of flux observation and research in Asia.

1 Progress in observation technique and evaluation method of flux research in Asia

The better understanding and evaluation of carbon sink/source in terrestrial ecosystems rely on the long-term measurements of carbon exchange between vegetation and atmosphere. Over several decades' flux observation and research in Asia, great progress has been made not only in the instrument and methodology of flux observation, but also in the evaluation of net ecosystem CO_2 exchange (NEE) under complex unfavorable conditions.

1.1 Observational technique of CO_2 flux

(i) Eddy covariance technique. In early studies, the eddy covariance technique (EC) is widely applied to measuring the transportation of energy and momentum and analyzing the turbulent structure within the boundary layer, which has constructed the theoretic and experimental foundation for the measurements of flux between vegetation and atmosphere in ecological studies[6]. Recently, EC has been regarded as a standard method to measure the carbon exchange in terrestrial ecosystems[6,7]. Baldocchi et al. reviewed the development and application of EC fully and detailedly[6], while attention should also be given to the great efforts and contributions by Asia scientists to the development in instruments and technique for flux observation.

Along with the development of sonic anemometer by Kaimal and Businger[8], Mitsuta also designed a sonic anemometer (DAT-600, KAIJO Co., Japan)[9], which is widely applied in AsiaFlux and provides a key well-performed instrument for flux observation with the practical sonic anemometer easily available after continuous improvement[10,11]. Ohtaki and Matsui firstly invented an infrared CO_2/H_2O analyzer, which could measure the fluctuations in CO_2 and water vapor concentrations synchronously[11,12]. There are two kinds of infrared CO_2/H_2O analyzer commonly used at present. One is the open-path infrared analyzer, such as LI7500 (Li-Cor Inc, USA) and Advanet-E009 (Advanet Co., Japan). The other is the close-path infrared CO_2/H_2O analyzer, such as LI7000 and LI6262 (Li-Cor Inc, USA), which is favored by flux observation community in AsiaFlux and is widely used to measure the carbon flux combined with a 3-dimensional sonic anemometer due to its preferable stability and strong environmental adaptability[13−18]. The performance of open-path and close-path eddy covariance system is also well compared in many studies[13,16,17], and Yasuda and Watanabe presented a new technique for flux correction due to the inadequate instrumental response in close-path system[16]. Recently, the open-path system gradually became popular in the long-term flux measurement with the improvement in its stability and environmental adaptability[6]. Both the open-path and close-path systems are conducted at forest sites of ChinaFLUX to compare the differences between the two systems.

(ii) Alternative methods for eddy covariance technique. Although the eddy covariance technique has become the standard method in flux observation in recent years, it is still necessary to study the alternative observation method to utilize the former routine meteorological data effectively, to overcome the potential constraints from unfavorable environmental conditions and eventually to improve the system adaptability in field observation. At present, the main alternative methods include vertical gradient method (VG)[19−22], bandpass eddy covariance technique (BP)[23−25] and relaxed eddy accumulation method (REA)[26−28].

For the vertical gradient method (VG), the scalar fluxes are estimated indirectly based on the aerodynamic principle and similarity theory by measuring the concentrations of CO_2 and H_2O at different heights. The VG method is more suitable for barren or low-vegetation surface and is difficult to apply over complex vegetation due to the CO_2 concentration gradient is often small in such ecosystem[6,13,29]. Yamamoto et al. compared the fluxes measured by eddy covariance and aerodynamic methods at Takayama cool-temperate broadleaf forest from 1994 to 1996[15]. Their results showed comparable fluxes measured with the two methods, thus the long-term seasonal variations of ecosystem NEE was estimated with the historical routine meteorological data when EC was not available[30]. Monji et al. presented two modified gradient methods for estimating CO_2 and H_2O fluxes, as one using the eddy diffusivity of sensible heat flux and the other using the general function of Richardson number Φ_m and Φ_h to obtain the flux-gradient relation[21]. Monji et al. also applied such a method to measure the fluxes of CO_2 and sensible heat over Mangrove forest during the wet and dry seasons[22].

The bandpass eddy covariance technique (BP) was designed for correcting the high-frequency loss due to the slow instrumental response, the tube attenuation in close-path system and the sensor separation between sonic anemometer and CO_2/H_2O analyzer[13]. Watanabe et al. presented an empirical frequency-response function that enabled the correction of scalar flux due to weak sensible heat conditions and slow instrumental response[25]. Their results showed that the fluxes measured with BP method were comparable to that with EC, and the improved bandpass eddy covariance method was suitable for the long-term fluxes measurement.

The relaxed eddy accumulation method (REA) is often used when only the slow response analyzer is available[13,26−28]. Hamotani et al. compared the fluxes measured with EC and REA and found a significant linear relationship between EC and REA methods[26]. After continuous measurement of NEE for 5 months over a needle forest, Monji et al. also agreed that REA was an feasible method to estimate ecosystem NEE when only the slow response instrument was available[13].

(iii) Chamber method. The net ecosystem exchange (NEE) is the balance between fluxes associated with photosynthetic assimilation by the foliage (gross ecosystem production, GEP) and ecosystem respiration (R_{eco})[7]. R_{eco} includes the autotrophic respiration (R_a) and heterogeneous respiration (R_h), and can be divided further into the component respiration from soil microbe, root, stem and leaf. It is very important to distinguish these different components of R_{eco} for understanding the underlying mechanism of ecosystem carbon cycle and improving the process-based carbon cycle model. As a reliable method, the chamber method has played a significant role in such studies[31].

The chamber method can be divided into static chamber and dynamic chamber. The static chamber is placed upon the soil or plants during the measurement and moved away after the measurement. However, the lips of dynamic chamber could open/close automatically to balance the inside and outside conditions of the chamber, which enabled the long-term and continuous measurements without moving the chamber. The dynamic chamber is complicated and expensive compared with the static chamber, which is cheap and convenient to move but difficult to be applied in the long-term measurement. Furthermore, the chamber system could use either a transparent chamber or a dark chamber. The dark chamber is commonly used to measure the ecosystem respiration in order to avoid the significant changes in temperature and moisture inside the transparent chamber.

The main methods in the measurement of respiration with chamber include static alkali absorption, static chamber-gas chromatogram (GC) and dynamic chamber-infrared analyzer method. Considering the technique and cost for observation, the former two methods are applied widely[31−33]. In recent years, the dynamic chamber-infrared analyzer method also becomes popular with the improvement in infrared analytical technique[34]. Miyama et al. designed an automated foliage chamber which was easily used to measure the seasonal pattern of CO_2 flux of foliage with good durability and low cost, and the results showed good agreement with that of the portable CO_2/H_2O analyzer (LCA-3)[35]. Liang et al. designed a multichannel automatic chamber system for long-term measurement of soil efflux and its spatial variability, which had been conducted in AsiaFlux and KoFlux and the results were comparable with LI6400-09 and soil CO_2 gradient system[36]. Recently, they further improved the automatic chamber for measuring the flux of plant stem and foliage.

CH_4 and N_2O are also very important greenhouse gases. Wang et al. had made great improvement in the static chamber system[31]. The gases were collected using the new system with syringes or gas sampling bags, and then the concentration of CH_4, CO_2 and N_2O was analyzed with the modified GC/FID and GC/ECD system[31]. Such a method has been widely applied to measuring the greenhouse gases on grassland[37,38], cropland[39], wetland[40] and forest[41,42] in China, and it is also an important method to measure soil respiration in ChinaFLUX. Besides, ecosystem NEE can also be estimated using such a method with the supplemental measurements of biomass, root respiration and above-ground respiration[39, 43].

1.2 Evaluation of net ecosystem carbon exchange

The measurement of net ecosystem CO_2 exchange (NEE) by EC is strictly restricted by the terrain status and meteorological conditions around the observation tower. Large deviation in NEE will appear when the environmental conditions fail to meet the assumption of eddy covariance technique. So it is an urgent task to establish the practical methodology for evaluating NEE in long-term flux measurement under unfavorable conditions.

(i) Averaging period and coordinate system. The choosing of averaging period and coordinate system of flux calculation could affect the quality of measured flux significantly. The excessively long averaging period will result in high frequency loss, while the excessively short period will induce not only the low frequency loss but also the increased noise[44].

The most commonly used coordinate system in early flux measurement and data processing is the rectangular coordinate system, sometimes called as 'natural' coordinate system[45] or the 'streamline' coordinate system[46]. In this coordinate system, the vertical velocity is constrained to zero in each averaging period through coordinate rotation, which will induce not only the severe bias or systematic underestimation of flux[47] but also apparent low frequency loss[44]. Recently, Wilczak et al.[46] and Paw U et al.[48] presented a new method of coordinate rotation, named the planar fit method (PF) which emphasized that the vertical velocity equaled zero over a set of many flux-averaging periods other than each period. Although the PF method is more reasonable than the former one, it is needed to test over complex terrain and evaluate its impact on long-term CO_2 fluxes and carbon budget[6]. Therefore, the 'natural' coordinate system is still commonly adopted in flux measurements in Asia in order to reduce the influence of horizontal and vertical advection[13−18,49,50]. Monji et al. indicated that the coordinate rotation exerted apparent effects on CO_2 flux, but whether to do the coordinate rotation or not should be defined according to the research objective and the required precision[13].

(ii) Estimation and evaluation of NEE over complex terrain. The CO_2 exchange between vegetation and atmosphere can be approximately measured with the eddy covariance technique under the conditions of unsteady atmosphere, homogenous vegetation and flat terrain. However, the complex topography and stable atmosphere are easy to induce the atmospheric storage, divergence and advection, which will considerably bias the estimation of NEE[6]. Up to now, there is no consensus on the exact reasons and standard correction methods to the 'distorted' NEE[6,47,51]. The correction of NEE is more concerned in Asia because of the complex topography and atmospheric stability.

At present, NEE is usually evaluated and corrected through two approaches; one is to compare with other alternative methods, such as aerodynamic method, energy balance method and chamber method. The other is the parallel comparison among several EC systems at the same site. Based on the analysis of energy balance state, Yamamoto et al. indicates that the NEE measured by EC was 40% overestimated due to the underestimation of respiration which resulted from the complex topography[15]. Saigusa et al. also indicated that the error of flux estimation might attain 24%−35% due to the influence of energy imbalance[17]. Kominami et al. had measured the CO_2 flux with two eddy covariance systems synchronously in the same watershed, and the results showed no apparent difference during the daytime between the two systems, while the nighttime flux measured from the tower in the valley was 36% higher than that from the tower on the ridge. Studies also showed that the eddy covariance flux of CO_2 including the canopy storage was 60% lower than that estimated by the chamber methods (F_{chm}), and the NEE estimated from the relationship between nighttime CO_2 flux and soil temperature (2 cm depth) obtained under high turbulence ($U_* \geqslant 0.25$ m s^{-1}) was still 32% lower than that of F_{chm}. The difference could be mainly ascribed to the advection effect rather than the canopy storage[52].

At present, it is difficult to quantify the influence of the factors affecting the nighttime flux due to the technical limitation. The flux correction is performed through the following indirect approaches: (1) Correct the eddy covariance flux with the parallel measurements by the chamber method; (2) Reestimate the nighttime flux by using the relationship between soil temperature and nighttime NEE under high turbulence[6]. The turbulent intensity is usually assessed by the friction velocity (U_*) and the U_* threshold shows apparent correlation with annual NEE[53], although there is no consensus on how to quantify the appropriate U_* threshold for each site. Yasuda et al.[14], Saigusa et al.[17] and Hirano et al.[18] indicated that the turbulent intensity had significant effect on the relationship between NEE and temperature, and the missed or abnormal nighttime flux could be estimated with the exponential relationship between nighttime flux and temperature under high turbulence. But such a relationship failed with the atmosphere becoming stabler and the turbulent intensity getting weaker. (3) Correct the eddy covariance flux with the statue of energy balance[54]. Both Yamamoto et al.[15] and Sagusa et al.[17] had applied this method to correcting NEE. However, such a method requires accurate measurement of available energy fluxes (sensible heat and latent heat fluxes), net radiation and soil heat flux. The energy fluxes measured by EC represent the average over relatively large area, while the soil heat flux measured near the flux tower could neither represent the spatial variability in large scale nor match the footprint of energy fluxes measured by EC[55]. Therefore, it is necessary to further analyze and validate the confidence and applicability of the energy balance approach in flux correction[6].

(iii) Fetch and footprint. The quantitative understanding of the spatial representativeness and the spatial distribution of fetch is the basic requirement for evaluating the regional representativeness of measured NEE and for scale conversion in many ecological models. As mentioned above, the NEE measured by

EC represents the average value within the area of flux contribution (Fetch). For the ecosystem with enough fetch, the measured NEE can be assumed as the real average NEE within the whole fetch, while the natural ecosystem often appears as patched and nested structures due to the impact of fragmentized landscape and complex terrain. The flux fetch will extend rapidly and even exceeds the range of investigated vegetation when the atmosphere gradually becomes stable[52]. While most models for evaluating fetch are based on eddy diffuse theory under the near-neutral atmospheric condition and are difficult to be applied to stable atmosphere. Meanwhile, the flux fetch also increases with the measurement height[55]. Hamotani et al. had used REA method to measure CO_2 and CH_4 fluxes at two heights (2 and 20 m) with a balloon over a paddy field, and the results showed much differences between the scalar fluxes at two heights due to the difference in fetch[27]. It is difficult to determine an appropriate measurement height at complex forest ecosystem to meet the requirement of enough fetch for EC, and the relationship between measurement height and the fetch is also hard to establish in field measurement[55].

The footprint refers to the spatial region that can be 'seen' by an eddy covariance system during the measurement. As an effective approach to evaluate the fetch quantitatively, footprint can quantify the spatial range of eddy covariance measurement and evaluate the regional representativeness of measured flux. Many footprint models have been developed, such as footprint analytical model, Lagrangian model and the footprint model based on large eddy simulation (LES)[56]. However these models need further improvement for lack of validation, complex calculation, weak practicability and insufficient analysis of the influencing factors such as canopy structure, surface heterogeneity, forest gap, forest edge and complex topography.

2 Observation and modeling of carbon flux in terrestrial ecosystems in Asia

2.1 Carbon sink/source in terrestrial ecosystems in Asia

One of the major tasks for flux observational network is to estimate the capacity of CO_2 sink/source and its spatio-temporal variation in terrestrial ecosystem. The CO_2 flux and its environmental controlling mechanism have been studied in different terrestrial ecosystems in Asia, such as cool-temperate deciduous forest[14,15,17,30,50,57], temperate mixed forest[51], temperate larch forest[18], Mangrove forest[28], tropic forest[49], alpine meadow[58] and cropland[59,60]. The capacity of CO_2 sink/source in some ecosystems has also been assessed. Table 1 shows the big difference in annual NEE between different ecosystems and the interannual variability within the same ecosystem. Although these studies have provided important information for evaluating the regional carbon budget in Asia, more information are required to reduce the large uncertainty in the results of earlier studies.

2.2 Seasonal and interannual variability in ecosystem CO_2 flux

The ecosystem CO_2 flux shows evident seasonal and interannual variability with the rhythm of vegetation succession and environmental change, the studies of which help much in understanding the biotic and environmental controls on ecosystem CO_2 flux and improving the existing process-based ecological models. The longest time-series dataset of flux observation has been obtained over a cool-temperate broadleaf forest at Takayama, Japan, which has been studied since 1994[30]. The observed NEE has shown obvious seasonal and inter-annual variations probably due to the following reasons: (1) the timing of snow melt and spring temperature affecting soil thawing and leaf out; (2) the length of the growing season and cloudiness that affecting the variability in CO_2 uptake; and (3) the variation in annual precipitation and its temporal distribution[30].

2.3 Modeling and scaling-up of ecosystem carbon cycle

The CO_2, H_2O and energy fluxes above plant canopies measured from flux tower can only represent the average status of the studied area[55]. Such data are mainly used for the several purposes: (1) to quantify the CO_2 and water vapor fluxes in interested ecosystem; (2) to analyze the processes of material and

Table 1 NEE of several forest ecosystems in Asia

Site	Vegetation type	MAT[a)] /℃	MAP[b)] /mm	Altitude /m	LAI[c)] /m² m⁻²	NEE[d)] /gC m⁻² a⁻¹	Period	Reference
Takayama	Cool temperate deciduous forest	7.3	2382	1420	3.5	−114	1994	[15]
						−65	1995	[15]
						−136	1996	[15]
						−214	07/1998—07/1999	[17]
Sapporo	Cool temperate deciduous forest	6.5	1100	180	4	−260	2000	[50]
						−357	06/1997—05/1998	[14]
Kawagoe	Warm temperate deciduous forest	15	1400	30	5.5	−300	1997—1999	[30]
Tomakomai	Temperate larch forest	7.7	1250	140		−220	07/2000—06/2001	[30]
		5.9	1265	140	2.1	−293	09/2000—08/2001	[18]
Fujiyoshida	Temperate evergreen coniferous forest	10			3.5	−330	2001	[30]
Kumamoto	Temperate evergreen coniferous forest	16				−570		[30]
Changbaishan	Temperate mixed forest	3.6	713	738	5.8	−184	2003	[61]
Qianyanzhou	Sub-tropical mixed plantation	17.8	1471	100		−553—−645	2003	[62]
Sakaerat	Tropical rainforest	24	2000		4	−600		[30]
Bukit Soeharto	Tropical rainforest	27	3300		4	−340—−460		[30]
Lhasa	Alpine meadow	−1.2	380	4800		−71.12	2000	[63]

a) MAT is the annual average temperature, b) MAP is the annual average precipitation (mm), c) LAI means the maximum LAI during the mid-season for deciduous forest, and 4) the negative NEE means the absorption of vegetation, while the positive means release from vegetation to atmosphere.

energy transportation within the boundary layer between vegetation and atmosphere; (3) to understand the underlying mechanism of carbon and water cycle in typical terrestrial ecosystems; and (4) to parameterize the process-based ecological models. The modeling and scale conversion is an indispensable and necessary approach in flux observation and carbon cycle research, together with the utilization of remote sensing technique. There are two approaches for scaling up flux data from tower to regional or even larger scale. One is to estimate the regional/global carbon and water budgets by integrating the flux tower data combined with elaborate classification map of land-use and land-cover. The second approach is to establish the carbon cycle model at regional scale based on the parameters derived from the flux sites, then the regional/global carbon and water budgets can be obtained with the support of spatialized vegetation and environment database. At present it is still difficult to estimate the carbon budget over the large region with the first approach because the flux tower measurements cannot be conducted across everywhere due to the complexity of the spatial pattern and the diversity of terrestrial ecosystems. Besides, the results from flux tower observation can't be applied to predicting the ecosystem response under future climatic scenario. Therefore, the second approach is assumed as the practicable method in scaling the flux data from site to region, and this method also retains the function of prediction in future scenarios.

The existing carbon cycle models can be separated into two types according to the structure and driving factors of the model. The first type of model is driven by satellite or remote sensing data and supported by spatialized vegetation and environment data, such as CASA (Carnegie Ames Stanford Approach), VPM (Vegetation Photosynthesis Model) and SiB2 (Revised Simple Biosphere Model). Piao et al. had simulated the spatial patterns of net primary production (NPP) of the terrestrial vegetation in China using CASA model, based on GIS and remote sensing technique and driven by meteorological data, such as climate, vegetation, soil and solar radiation data[64]. Xiao et al. had also simulated the seasonal and inter-annual variation of GPP in an evergreen conifer forests in Maine with VPM model using two improved vegetation indices EVI (Enhanced Vegetation Index) and LSWI (Land Surface Water Index)[65].

The other type of model is the process-based mechanism mode, such as Chikugo[66], CENTURY[67], FOREST-BGC[68], AVIM[69], TEM[70], CEVSA[71], and Sim-CYCLE[72] which are driven by climatic data and mainly used to simulate the scalar and energy fluxes between vegetation and atmosphere and the vegetation productivity. These models can exhibit the response of vegetation to environmental changes, and can simulate and predict ecosystem carbon cycle in the past or future. The simulations by these models have better reliability at small scale because they are usually established upon the process-based studies and the measured flux data. Besides, the spatial patterns of ecosystem carbon and water cycle can also be derived from such models by using the spatial parameterization and spatialized vegetation and environmental data, which also enables the effective integration with GCMs.

Chikugo model, which was presented by Uchijima and Seino and well validated with the inventory productivity data in each county in Japan, was widely used in Asia. The first spatial distribution map of net primary production (NPP) in Japan was derived from Chikugo model, and the effects of increasing atmospheric CO_2 and climate variability on NPP were also analyzed[66]. Chikugo model is semi-empirical statistic model, in which the water use efficiency (WUE) is assumed as a constant. However, recent studies indicated that WUE have great variability with plant species. A WUE evaluation model (SMPT-SB) is advanced based on the integrated model of plant photosynthesis-transpiration[73–75]. Ji also developed a biophysical model (AVIM) to simulate the material transportation through the atmosphere-vegetation-soil continuum and to estimate the carbon flux at single site or over large region. And favorable results have been obtained from the simulation of CO_2 flux and NPP in the semi-arid steppe of Inner-Mongolia, Changbaishan mixed forest and cropland in north of China[69]. Cao and Woodward developed CEVSA (Carbon Exchange between Vegetation, Soil, and the Atmosphere) model to study the terrestrial carbon exchange and its response to climatic changes, based on the processes of photosynthesis, carbon allocation within plant and the decomposition of litter and soil organic carbon[71]. Ito and Oikawa presented a new terrestrial carbon cycle model (Sim-CYCLE) to simulate the carbon dynamic in various terrestrial ecosystems and to predict their responses to global environmental change[72]. They also simulated the spatio-temporal patterns of CO_2 exchange between vegetation and atmosphere by combining the Sim-CYCLE model with the stable carbon isotopic method.

The ecological scale appears multi-dimensional characteristics, i.e. the spatial scale, temporal scale and functional scale, which is distinguishing but also related to spatial and temporal scales. Zhang et al. presented a model for estimating CO_2 flux in a wheat field at regional scale using the remote sensing and micro-meteorological data[76]. Xiao et al. have attempted to estimate the GPP of a forest ecosystem by scale up from the plot-scale measurement of CO_2 flux to regional scale with VPM model[65]. But there still exist many unresolved issues in the scale conversion, and these issues would still be important scientific tasks for regional flux observation and research in future.

3 Research advances in ChinaFLUX

The long-term and continuous flux measurement has been conducted over 10 different terrestrial ecosystems in China since the establishment of ChinaFLUX in Oct 2002, including forest, grassland and cropland ecosystems. For the first time, ChinaFLUX acquired the data of CO_2, water vapor and energy fluxes and meteorological variables, which provides important data basis for the carbon cycle research. Great achievements have been obtained in EC technique, ecosystem flux patterns and model improvement.

3.1 Eddy covariance technique

(i) Flux averaging period and coordinate rotation. Two important technique problems in flux measurement are how to choose the appropriate averaging period for flux calculation and the method of coordinate rotation according to the specific environmental conditions of flux site. Sun et al. proposed a method to quantify the appropriate averaging period in flux calculation[77] and the results indicated that the surface status has great effect on the appropriate averaging period. For the flat cropland, there was no much difference with the averaging period from 10 to 60 min; while 30—60 min was suitable for Changbaishan forest site, which showed an increasing NEE with the lengthened averaging period. It indicated that an averaging period of 30 min was appropriate for most sites of ChinaFLUX.

As for the method of coordinate rotation, studies[78,79] have shown that the double rotation, triple rotation and planar fit method could all correct the flux properly, and the magnitude of the correction term was mainly influenced by surface slope, slope orientation, wind speed and wind direction[78]. The planar fit method seems better than the triple rotation method at Changbaishan forest site since the triple rotation is very likely to result in the underestimation in NEE due to the tilt of both instrument and surface[79].

(ii) NEE evaluation and correction. The evaluation and correction of NEE measured under unfavorable atmospheric condition are very urgent tasks that are not well solved yet. The common criteria of flux evaluation include the spectral analyses, flux variance similarity and energy balance closure. Wen et al. assessed the quality of fluxes data measured at two heights at the Qianyanzhou forest site[80]. The results 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. The existing eddy covariance systems were able to resolve the fluctuations associated with small eddies and would not induce an obvious underestimation of the measured turbulent 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. The optimal criterion of friction velocity was greater than 0.2—0.3 m s^{-1} for valid measurement at nighttime so that the eddy covariance flux measurements were under the high turbulent condition with an energy balance closure reaching 72%—81%[80]. The negative NEE, which meant absorption by vegetation, often appeared during the nighttime in winter at Changbaishan forest, which probably resulted from the effects of pressure fluctuation and horizontal advection under strong wind conditions[81]. Wu et al. considered that the underestimation of NEE because of the limitation in frequency response was 3.0% and 9.0% in daytime and nighttime, respectively, which was closely related to atmospheric stability[78]. It was also found that the CO_2 flux loss due to the effect of advection could be mainly ascribed to nocturnal vertical advection[78]. However, more studies are needed to evaluate and correct the measured NEE due to the complex topography in most sites of ChinaFLUX.

(iii) Comparison between OPEC and CPEC. Both OPEC and CPEC systems are applied in flux measurement of ChinaFLUX, and the parallel comparison is conducted at Changbaishan and Qianyanzhou site to examine the difference between the two systems. The results showed that both the spectral and cospectral slopes were consistent with the expected −2/3 and −4/3 slope, respectively, in the inertial subrange of measured data from two systems[80,82]. The NEE measured by CPEC was a little less than that by OPEC, while the diurnal variation of NEE was similar[82]. These studies showed that the measurements from the OPEC and CPEC could be used for the inter-verification between the two systems and for gap filling in long-term flux measurement.

(iv) Evaluation on energy balance. Energy balance is often regarded as an important criterion for evaluating the data quality of fluxes measured with EC. Energy balance closures in ChinaFLUX were evaluated with the methods of OLS (Ordinary Least Squares), RMA (Reduced Major Axis), energy balance ratio (EBR) and the frequency distribution of relative errors in energy balance (δ)[83]. The results showed that the energy imbalance was prevalent in ChinaFLUX, and the imbalance was severer during nighttime than daytime and was improved with increasing of friction velocity. The probably reasons for energy imbalance include sampling errors, systematic instrument bias, neglected energy sinks, low and high frequency loss of turbulent fluxes and advection effects of heat and water vapor[83], which affect not only the measurement of NEE but also the heat storage in the soil and vegetation. At present, it is still very difficult to identify the respective contribution from different factors. Therefore, the state of energy balance can be an important reference criterion but not an absolute criterion for evaluating data quality in flux measurement[80].

3.2 Environmental controls on carbon flux

The studies on the diurnal, seasonal and annual flux variation and their environmental controlling mechanism could help understand the ecosystem process for model improvement. The leaf scale study by Shi et al. indicated that α_A was mainly influenced by temperature and the ratio of CO_2 and O_2 partial pressure ($[CO_2]/[O_2]$), shown as an linear increasing with temperature and a hyperbolic relationship with C_i with when $[O_2]$ is constant[84]. The α_A at Tibetan Plateau was more sensitive to the increase of CO_2 than that at low elevation regions[84]. At ecosystem scale, the dependence of daytime NEE could be well described with the hyperbolic model[61,62,85,86], while the temperature and water availability could affect the seasonal variation of NEE greatly[61,62]. The exponential model is often used to describe the relationship between nighttime NEE (i.e. ecosystem respiration) and temperature, and the multiplicative model is usually used to assess the integrated influence of both soil water content and temperature on ecosystem respiration. For example, NEE = $f(T)f(S_w)$, where $f(T)$ and $f(S_w)$ are the temperature and soil moisture function of ecosystem respiration, respectively. Yu et al. indicated that although temperature was a dominant factor that affects the ecosystem respiration, soil water content could be the dominant limiting factor under severe drought[87]. They also found that Q_{10} model was more sensitive to soil moisture than the commonly used multiplicative model, and it could well simulate the seasonal variation of ecosystem respiration.

3.3 Soil respiration

Soil respiration is a major component of ecosystem respiration and it has become one of the key issues in global carbon research because of the great uncertainty in the ecological process and mechanism of soil respiration due to the limitation in measurement technique. With the flux measurement with EC, the chamber method is also used to measure the CO_2 flux at ground surface at 16 sites in China. Sha et al.[88], Zhou et al.[89] and Zhang et al.[63] had studied soil respiration in Xishuangbanna seasonal rainforest, Dinghushan tropical forest and an alpine meadow, respectively. For Xishuangbanna forest, the contributions from the soil, litter and short-vegetation to the total CO_2 flux at the ground surface were 65.2%, 22.3% and 12.5%, respectively. The soil respiration increased with the soil temperature exponentially but showed parabola variations with soil moisture, which indicated that the higher soil moisture was not favor to soil respiration[88]. The annual average CO_2 flux at the ground surface in monsoon forest, mixed forest and pine forest at Dinghushan site were 359.7, 233.33 and 178.56 mg m^{-2} h^{-1}, respectively; while the CO_2 flux from the decomposition of litter were 116.28, 167.27 and 73.76 mg m^{-2} h^{-1} for the three forest, respectively. The highest CO_2 flux from the decomposition of litter in the missed forest was related to the high storage of litter on the surface[89]. The two-year measurement of soil respiration in the plateau meadow showed that the diurnal variation of soil respiration appeared obviously higher emission during daytime and lower emission during nighttime, fluctuating from minimum at 05:00 to maximum at 14:00 of local time. The soil respiration is usually high in summer and decreases sharply in winter, and results also indicate that the alpine meadow ecosystem was a carbon sink[63, 86].

3.4 Modeling and simulation of CO_2 flux

The process-based model plays an important role in the scale up from tower to region. The establishment and improvement of model also receives great attention in ChinaFLUX along with the flux measurement. Cao et al. indicated that the carbon cycle research in future should put emphasis on trying to understand and quantify of the effects of the interactions between the ecological processes at different scales on the carbon flux with the methods of multi-scale experiments and cross-scale mechanism models. The data-model fusion had great potential application in carbon cycle research in future, including: (1) the establishment of the cross-scale mechanism models from the 'forward' and 'inversion' with multi-scale measurements; (2) the validation of models on multi-scale with different data; and (3) the estimation and prediction of the variations in ecosystem carbon cycle with the mechanism model driven and steered by dynamic data[90]. Wang et al. developed the BEPSh model to simulate daily variation of ecosystem exchange at half-hour step based on the process-based BEPS model, and the model was used to simulate the CO_2, H_2O and energy fluxes at Changbaishan temperate broad-leaved Korean pine forest[91]. The results showed that the forest was sensitive to climate variability, and its capacity of carbon sequestration would be weakened under the global warming according to the analysis under different climate scenarios[91]. Based on the SMPT-SB model, Ren et al. developed the ecosystem photosynthesis-transpiration coupling model by simulating the canopy light distribution, and the CO_2 and H_2O fluxes were scaled from single leaf to canopy with the model. SMPT-SB model could be used as a basic coupling model of carbon and water cycle in soil-plant-atmosphere continuum, which was simpler and easy to be used compared with other process-based models[92]. Furthermore, Zhang et al. constructed a coupling model for simulating plant photosynthesis and evapotranspiration (CPCEM), and the diurnal and seasonal patterns of CO_2 and H_2O fluxes over a cropland were well simulated[93].

4 Prospects of the flux observation and research in Asia

Although great achievements have been made in flux measurement and research in Asia, more studies are still necessary for understanding the variable mechanism of key process of carbon cycling, evaluating the spatial distribution of C sink/source in Asia and its response to environmental change, and developing the integrated model of carbon cycle in terrestrial ecosystems. At present, the urgent tasks of flux observation and research in Asia include: (1) to determine a universal method for flux evaluation and correction, especially over complex topography; (2) to elucidate further the relationships between the key ecological processes of ecosystem carbon cycle; and (3) to develop and improve the process-based models for scaling up from flux tower to region, which could help evaluate the spatial distribution of carbon sink/source and its response to environmental changes and provide data support for the establishment of international framework of reducing carbon emission. In order to address the scientific issues mentioned above, the following research work needs to be furthered.

4.1 NEE correction and estimation under complex terrain

Most flux sites in Asia are situated on complex terrain, which could not meet the basic assumption (horizontally homogeneous surface for sufficiently long upwind area) for proper application of the eddy covariance technique, therefore it is urgent to establish reasonable theory and method to correct flux over complex terrain or during nighttime. This problem can be addressed or improved with attention to the following 6 aspects: (1) the parallel comparison between EC, chamber method and other alternative methods, (2) the comparison of CO_2 flux estimated by EC and spatial CO_2 measurements with tethered balloon or airplane in ABL, (3) the comparison CO_2 flux estimated by EC and biomass survey; (4) analysis of the footprint climatology and its scale effect, (5) the numerical simulation of turbulent transportation characteristics and the spatial distribution of fetch; and (6) the improvement of ecosystem carbon and water coupling mechanism model.

4.2 The integration of flux observation, stable isotope method, remote sensing

The ecosystem carbon cycle is affected by the comprehensive influence of physical, biotic, ecological factors and human activities. It has exhibited high heterogeneity and spatio-temporal variability. The integration of multi-scale, multi-process and multi-discipline research on ecosystem carbon and water cycling is necessary for understanding the complex relationship between the varying mechanism of the key ecological process in carbon cycle and the environmental factors. Stable isotopic technique plays a unique role in flux evaluation because it could quantitatively distinguish the respective contributions from different components of ecosystem to the carbon, water and energy fluxes, and it has been widely applied in the research of ecosystem carbon cycle[94—96]. However, the stable isotopic technique is seldom used in former studies and it should be intensified in flux observation and research in Asia. The study of ecosystem ecophysiological process provides not only the necessary method for explanation and demonstration of flux measurement, but also the foundation for the establishment of process-based model and the improvement in the use efficiency of flux data. Therefore, the elaborate observation and research of photosynthesis, plant growth, litter decomposition and ecosystem respiration is very helpful to promoting the flux observation and research. The remote sensing (RS), numerical simulation and geographic information system (GIS) are indispensable techniques in scale up from plot-scale to region scale and the prediction of future trend. A comprehensive and regional flux research network in the future should be based on the ecological research network and combined with the stable isotope measurement, the ecological process investigation, remote sensing and modeling and its improvement (fig. 2).

4.3 Regional cooperation of flux observation and research in Asia

Although the carbon flux has been measured over many terrestrial ecosystems in Asia, the spatial distribution of existing flux sites is still insufficient to elucidate the responses of those greenhouse gases to environmental change in different ecosystems and the contribution of terrestrial ecosystem in Asia to global carbon budget. It is more important to intensify the study on the technique of scaling up from plot-scale measurement to regional scale along with the increasing flux sites in future, and enhance assimilation of flux data and model. Besides, data sharing between different regional networks should also be furthered. Therefore, it is necessary to establish the Joint Committee of Asian Flux Network in the Asia-Pacific region in order to promote the cooperation and data sharing among regional networks such as AsiaFlux, KoFlux, ChinaFLUX and OzFlux, and eventually form a uniform guide for flux measurement, organize technical training and inter-calibration of flux meas-

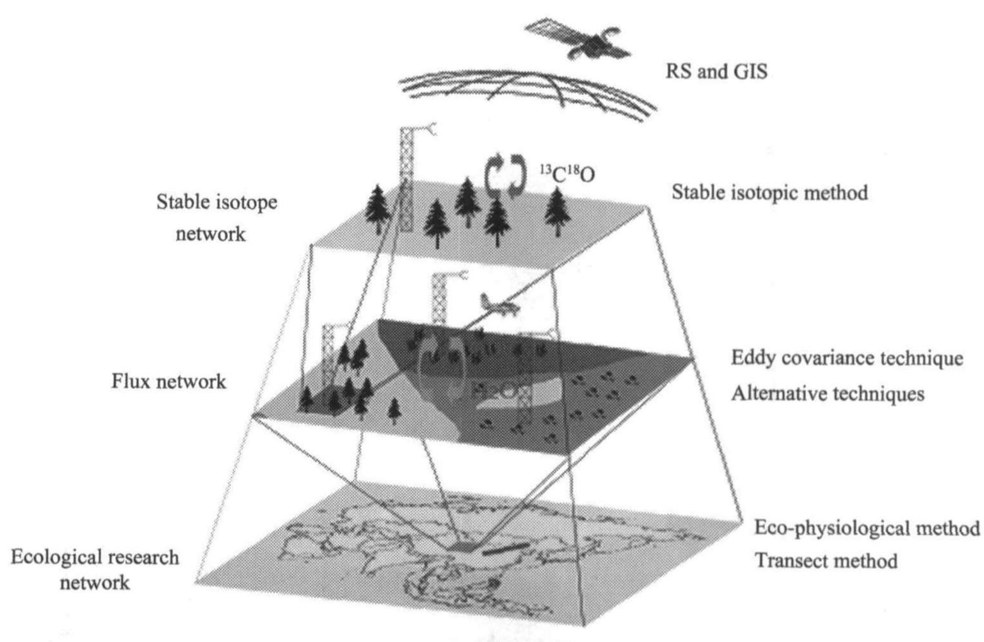

Fig. 2. Structure of the integrated regional flux network.

urement systems and promote the communication of ideas and data by supporting project scientists, workshops and visiting scientists.

Acknowledgements This study was supported by the Knowledge Innovation Project of the Chinese Academy of Sciences (Grant No. KZCX1-SW-01-01A) and the National Key Research and Development Program (Grant No.2002CB412501).

References

1. IPCC, Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (eds. Houghton, J. T., Ding, Y., Griggs, D. J.), New York: Cambridge University Press, 2001.
2. Goulden, M. L., Munger, J. W., Fan, S. M. et al., Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability, Science, 1996, 271: 1576—1578.
3. Schimel, D. S., House, J. I., Hibbard, K. A. et al., Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, Nature, 2001, 414: 169—172.
4. Global Carbon Project, Science framework and implementation. Earth System Science Partnership (IGBP, IHDP, WCRP, DIVERSITAS) Report No. 1; Global Carbon Project Report No. 1, Canberra, 2003.
5. Baldocchi, D., Falge, E., Gu, L. et al., Fluxnet: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, Bulletin of the American Meteorological Society, 2001, 82: 2415—2434.
6. Baldocchi, D., Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, Global Change Biology, 2003, 9: 479—492.
7. Valentini, R., Matteucci, G., Dolman, A. J. et al., Respiration as the main determinant of carbon balance in European forests, Nature, 2000, 404: 861—865.
8. Kaimal, J. C., Businger, J. A., A continuous wave sonic anemometer-thermometer, Journal of Applied Meteorology, 1963, 2: 156—164.
9. Mitsuda, Y., Sonic anemometer-thermometer for general use, Journal of the Meteorological Society of Japan, 1966, 44: 12—24.
10. Kaimal, J. C., Gaynor, J. E., Zimmerman, H. A. et al., Minimizing flow distortion errors in a sonic anemometer, Boundary-Layer Meteorology, 1990, 53: 103—115.
11. Ohtaki, E., Matsui, T., Infrared device for simultaneous measurement of fluctuations of atmospheric carbon dioxide and water vapor, Boundary-Layer Meteorology, 1982, 24: 109—119.
12. Ohtaki, E., Application of an infrared carbon dioxide and humidity instrument to studies of turbulent transport, Boundary-Layer Meteorology, 1984, 29: 85—107.
13. Monji, N., Plants and Micrometeorology-Turbulence and Fluxes in Plant Atmosphere, Osaka: Osaka Municipal Universities Press, 2003.
14. Yasuda, Y., Watanabe, T., Ohtani, Y. et al., Seasonal variation of CO_2 flux over a broadleaf deciduous forest, Japan Society of Hydrology and Water Resources, 1998, 11 (6): 575—585.
15. Yamamoto, S., Murayama, S., Saigusa, N. et al., Seasonal and inter-annual variation of CO_2 flux between a temperate forest and the atmosphere in Japan, Tellus B, 1999, 51: 402—413.
16. Yasuda, Y., Watanabe, T., Comparative measurements of CO_2 flux over a forest using closed-path and open-path CO_2 analyzers, Boundary-Layer Meteorology, 2001, 100: 191—208.
17. Saigusa, N., Yamamotoa, S., Murayama, S. et al., Gross primary production and net ecosystem exchange of a cool-temperate deciduous forest estimated by the eddy covariance method, Agricultural and Forest Meteorology, 2002, 112: 203—215.
18. Hirano, T., Hiratai, R., Fujinuma, Y. et al., CO_2 and water vapor exchange of a larch forest in northern Japan, Tellus B, 2003, 55: 244—257.
19. Inoue, I., An aerodynamic measurement of photosynthesis over a paddy field, Proc. of the 7th Japan National Congress of Applied Mechanics (in Japan), 1958, 211—214.
20. Yabuki, K., Aoki, M., The effect of wind speed on the photosynthesis of rice field, Ecophysiology of Photosynthetic Productivity (eds. Monsi, M., Saeki, T.), Tokyo: Tokyo University Press, 1978, 152—159.
21. Monji, N., Hamotani, K., Tosa, R. et al., CO_2 and water vapor flux evaluations by modified gradient methods over a Mangrove forest, Journal of Agricultural Meteorology, 2002a, 58 (2): 63—69.
22. Monji, N., Hamotani, K., Hamada, Y. et al., Exchange of CO_2 and heat between Mangrove forest and the atmosphere in wet and dry seasons in southern Thailand, Journal of Agricultural Meteorology, 2002b, 58 (2): 71—77.
23. Ohtaki, E., On the similarity in atmospheric fluctuations of carbon dioxide, water vapor and temperature over vegetated fields, Boundary-Layer Meteorology, 1985, 32: 25—37.
24. Yasuda, Y., Watanabe, T., Yamaoki, K. et al., Measurement of scalar flux from a forest using the bandpass covariance method, Journal of Agricultural Meteorology, 1997, 52: 493—496.
25. Watanabe, T., Yamanoi, K., Yasuda, Y., Testing of the bandpass eddy covariance method for a long-term measurement of water vapor flux over a forest, Boundary-Layer Meteorology, 2000, 96: 473—491.
26. Hamotani, K., Uchida, Y., Monji, N. et al., A system of the relaxed eddy accumulation method to evaluate CO_2 flux over plant canopies, Journal of Agricultural Meteorology, 1996, 52: 135—139.
27. Hamotani, K., Yamamoto, H., Monji, N. et al., Development of a mini-sonde system for measuring trace gas fluxes with the REA method, Journal of Agricultural Meteorology, 1997, 53: 301—306.
28. Monji, N., Hamotani, K., Hirano, T. et al., CO_2 and heat exchange of a mangrove forest in Thailand, Journal of Agricultural Meteorology, 1996, 52: 149—154.
29. Raupach, M. R., Anomalies in flux-gradient relationships over forests, Boundary-Layer Meteorology, 1979, 16: 467—486.
30. Yamamoto, S., Saigusa, N., Murayama, S. et al., Findings through ten-years flux measurement at Takayama and remaining subjects, Proc. of Synthesis Workshop On The Carbon Budget in Asian Monitoring Network, the Decennial Anniversary of the Observation at Takayama Site, 2003, 15—18.
31. Wang, Y. S., Wang, Y. H., Quick measurement of CH_4, CO_2 and N_2O emissions from a short-plant ecosystem, Advances in Atmospheric Sciences, 2003, 20(5): 842—844.

32. Dong, Y. S., Qi, Y. C., Luo, J. et al., Experimental study on N_2O and CH_4 fluxes from the dark coniferous forest zone soil of the Gongga Mountain, China, Science in China, Series D, 2003, 46(3): 285—295.
33. Dong, Y. S., Zhang, S., Qi, Y. C. et al., Fluxes of CO_2, N_2O and CH_4 from a typical temperate grassland in Inner Mongolia and its daily variation, 2000, 45: 1590—1594.
34. Liang, N., Inoue, G., Fujinuma, Y., A multichannel automated chamber system for continuous measurement of forest soil efflux, Tree Physiology, 2003, 23: 825—832.
35. Miyama, T., Kominami, Y., Tamai, K. et al., Automated foliage chamber method for long—term measurement of CO_2 flux in the uppermost canopy, Tellus B, 2003, 55: 322—330.
36. Liang, N. S., Nakadai, T., Hirano, T. et al., In situ comparison of four approaches to estimating soil CO_2 efflux in a northern larch (*Larix kaempferi* Sarg.) forest, Agricultural and Forest Meteorology, 2003b, 123: 97—117.
37. Wang, Y. S., Hu, Y. Q., Ji, B. M. et al., An investigation on the relationship between emission/uptake of greenhouse gases and environmental factors in semiarid grassland, Advances in Atmospheric Sciences, 2003, 20(1): 119—127.
38. Wang, Y. S., Hu, Y. Q., Ji, B. M. et al., Research of grazing effects on greenhouse gas emission in Inner Mongolian grasslands, China Environmental Science, 2002, 22: 490—494.
39. Zheng, X. H., Xu, Z. J., Wang, Y. S. et al., Determination of net exchange of CO_2 between paddy fields and atmosphere with static poaque chamber based measurements, Chinese Journal of Applied Ecology, 2002, 13: 1240—1244.
40. Hao, Q. J., Wang, Y. S., Song, C. C., Study of CH_4 emission from wetlands in Sanjiang plain, Journal of Soil and Water Conservation, 2004, 18(3): 194—199.
41. Xiao, D. M., Wang, M., Wang, Y. S. et al., Fluxes of soil carbon dioxide, nitrous oxide and firedamp in broad-leaved Korean pine forest, Journal of Forestry Research, 2004, 15(2): 107—112.
42. Zhou, C. Y., Zhang, D. Q., Wang, Y. S. et al., Diurnal variations of fluxes of the greenhouse gases from a coniferous and broad-leaved mixed forest soil in Dinghushan, Acta Ecologica Sinica, 2004, 24: 1741—1745.
43. Zou, J. W., Huang, Y., Zheng, X, H. et al., Static opaque chamber-based technique for determination of net exchange of CO_2 between terrestrial ecosystem and atmosphere, Chinese Science Bulletin, 2004, 49: 381—388.
44. Finnigan, J. J., Clement, R., Malhi, Y. et al., A re-evaluation of long-term flux measurement techniques Part I: Averaging and coordinate rotation, Boundary-Layer Meteorology, 2003, 107: 1—48.
45. Kaimal, J. C., Finnigan, J. J., Atmospheric Boundary Layer Flows—Their Structure and Measurement (in the United States), New York: Oxford University Press, 1994, 289.
46. Wilczak, J. M., Oncley, S. P., Stage, S. A., Sonic anemometer tilt correction algorithms, Boundary-Layer Meteorology, 2001, 99: 127—150.
47. Lee, X., On micrometeorological observations of surface-air exchange over tall vegetation, Agricultural and Forest Meteorology, 1998, 91: 39—49.
48. Paw U, K. T., Baldocchi, D. D., Meyers, T. P. et al., Correction of eddy-covariance measurements incorporating both advective effects and density fluxes, Boundary-Layer Meteorology, 2000, 97: 487—511.
49. Yasuda, Y., Ohtani, Y., Watanabe, T. et al., Measurement of CO_2 flux above a tropical rain forest at Pasoh in Peninsular Malaysia, Agricultural and Forest Meteorology, 2003, 114: 235—244.
50. Nakai, Y., Kitamura, K., Suzuki, S. et al., Year-long carbon dioxide exchange above a broadleaf deciduous forest in Sapporo, Northern Japan, Tellus B, 2003, 55: 305—312.
51. Massman, W. J., Lee, X., Eddy covariance corrections and uncertainties in long-term studies of carbon and energy exchanges, Agricultural and Forest Meteorology, 2002, 113: 121—144.
52. Kominami, Y., Miyama, T., Tamai, K. et al., Characteristics of CO_2 flux over a forest on complex topography, Tellus. B, 2003, 55: 313—321.
53. Aubinet, M., Grelle, A., Ibrom, A. et al., Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology, Advances in Ecological Research, 2000, 30: 113—175.
54. Twine, T. E., Kustas, W. P., Norman, J. M. et al., Correcting eddy-covariance flux underestimates over a grassland, Agricultural and Forest Meteorology, 2000, 103: 279—300.
55. Schmid, H. P., Source areas for scalar and scalar fluxes, Boundary-Layer Meteorology, 1994, 67: 293—318.
56. Schimel, H. P., Footprint modeling for vegetation atmosphere exchange studies: A review and perspective, Agricultural and Forest Meteorology, 2002, 113: 159—183.
57. Choi, T., Kim, J., Lim, J. H., CO_2 exchange in Kwangneung broadleaf deciduous forest in a hilly terrain in the summer of 2002, Korea Journal of Agricultural and Forest Meteorology, 2003, 5(2): 70—80.
58. Gu, S., Tang, Y. H., Du, M. Y. et al., Short-term variation of CO_2 flux in relation to environmental controls in an alpine meadow on the Qinghai-Tibetan Plateau, Journal of Geophysical Research, 2003, 108(D21): 4670.
59. Wang, S. S., Zhu, Z. L., Sun, X. M., Characteristics of energy and mass exchanges in the wheat field of Lhasa, Xizang (Tibet), Science in China, Series D, 1996, 39(4): 418—424.
60. Miyata, A., Leuning, R., Denmead, O. T. et al., Carbon dioxide and methane fluxes from an intermittently flooded paddy field, Agricultural and Forest Meteorology, 2000, 102: 287—303.
61. Guan, D. X., Wu, J. B., Yu, G-R. et al., Meteorological control on CO_2 flux above broad-leaved Korean pine forest in Changbai Mountains, Science in China, Series D, 2005, 48(Supp. I): 116—122.
62. Liu, Y. F., Song, X., Yu, G-R., et al., Seasonal variation of CO_2 flux and its environmental factors in evergreen coniferous plantation, Science in China, Series D, 2005, 48(Supp. I): 123—132.
63. Zhang, X. Z., Shi, P. L., Liu, Y. F. et al., Experimental study on soil CO_2 emission in the alpine grassland ecosystem on Tibetan Plateau, Science in China, Series D, 2005, 48(Supp. I): 218—224.
64. Piao, S. L., Fang, J. Y., Application of CASA model to the estimation of Chinese terrestrial primary productivity, Acta Phytoecologica Sinica, 2001, 25(5): 603—608.
65. Xiao, X. M., Hollinger, D., Aber, J., Satellite-based modeling of gross primary production in an evergreen needle leaf forest, Re-

mote Sensing of Environment, 2004, 89: 519—534.
66. Uchijima, Z., Seino, H., Agroclimatic evaluation of net primary productivity of natural vegetations (1) Chikugo model for evaluating net primary productivity, Journal of Agricultural Meteorology, 1985, 40(4): 343—352.
67. Parton, W. J., Schimel, D. S., Cole, C. V. et al., Analysis of factors controlling soil organic levels of grasslands in the Great Plains, Soil Science Society of America Journal, 1987, 51: 1173—1179.
68. Running, S. W., Coughlan, J. C., A general model of forest ecosystem processes for regional applications, I. Hydrologic balance, canopy gas exchange and primary production processes, Ecological Modelling, 1988, 42: 125—154.
69. Ji, J. J., Yu, L., A Simulation Study of Coupled Feedback Mechanism between Physical and Biogeochemical Processes at the Surface, Chinese Journal of Atmospheric Sciences, 1995, 23(4): 439—448.
70. Raich, J. W., Rastetter, E. B., Melillo, J. M. et al., Potential net primary productivity in south America: Application of a global model, Ecological Application, 1991, 4: 399—429.
71. Cao, M. K., Woodward, F. I., Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change, Global Change Biology, 1998, 4: 185—198.
72. Ito, A., Oikawa, T., A simulation model of the carbon cycle in land ecosystems (Sim-CYCLE): A description based on dry-matter production theory and plot-scale validation, Ecological Modelling, 2002, 151: 143—176.
73. Yu, G-R., Wang, Q. F., Zhuang, J., Modeling the water use efficiency of soybean and maize plants under environmental stresses: application of a synthetic model of photosynthesis-transpiration based on stomatal behavior, Journal of Plant Physiology, 2004, 161(3): 303—318.
74. Yu, G-R., Tatsuaki, K., Zhuang, J. et al., A coupled model of photosynthesis-transpiration based on the stomatal behavior for maize (*Zea mays* L.) grown in the field, Plant and Soil, 2003, 249(2): 401—415.
75. Yu, G-R., Zhuang, J., Yu, Z. L., An attempt to establish a synthetic model of photosynthesis-transpiration based on stomatal behavior for maize and soybean plants grown in field, Journal of Plant Physiology, 2001, 158: 861—874.
76. Zhang, R. H., Sun, X. M., Zhu, Z. L., A remote sensing model of CO_2 flux for wheat and studying of regional distribution, Science in China, Series D, 1999, 30(2): 325—336.
77. Sun, X. M., Zhu, Z. L., Xu, J. P. et al., Determination of averaging period parameter and its effects analysis for eddy covariance measurements, Science in China, Series D, 2005, 48(Supp. I): 33—41.
78. Zhu, Z. L., Sun, X. M., Zhou, Y. L. et al., Correcting method of eddy covariance fluxes over non-flat surfaces and its application in ChinaFLUX, Science in China, Series D, 2005, 48(Supp. I): 42—50.
79. Wu, J. B., Guan, D. X., Sun, X. M. et al., Eddy flux corrections for CO_2 exchange in broad-leaved Korean pine forest of Changbai Mountains, Science in China, Series D, 2005, 48(Supp. I): 106—115
80. Wen, X. F., Yu, G-R., Sun, X. M. et al., Turbulence flux measurement above the overstory of a subtropical *Pinus* plantation over the hilly region in southeastern China, Science in China, Series D, 2005, 48(Supp. I): 63—73.
81. Zhang, J. H., Han, S. J., Sun, X. M. et al., UU* filtering of nighttime net ecosystem CO_2 exchange flux over forest canopy under strong wind in wintertime, Science in China, Series D, 2005, 48(Supp. I): 85—92.
82. Song, X., Yu, G-R., Liu, Y. F. et al., Comparison of flux measurement by open-path and close-path eddy covariance systems, Science in China, Series D, 2005, 48(Supp. I): 74—84.
83. Li, Z. Q., Yu, G. R., Wen, X. F. et al., Energy balance closure at ChinaFLUX sites, Science in China, Series D, 2005, 48(Supp. I): 51—62
84. Shi, P. L., Zhang, X. Z., Zhong, Z. M., Apparent quantum yield of photosynthesis of winter wheat and its response to temperature and intercellular CO_2 concentration under lower atmospheric pressure on the Tibetan Plateau, Science in China, Series D, 2005, 48(Supp. I): 182—188.
85. Xu, L. L., Zhang, X. Z., Shi, P. L. et al., Establishment of apparent quantum yield and maximum ecosystem assimilation on Tibetan Plateau alpine meadow ecosystem, Science in China, Series D, 2005, 48(Supp. I): 141—147.
86. Xu, S. X., Zhao, X. Q., Li, Y. N. et al., Characterizing CO_2 fluxes for growing and non-growing seasons in a shrub ecosystem on the Qinghai-Tibet Plateau, Science in China, Series D, 2005, 48(Supp. I): 133—140.
87. Yu, G. R., Wen, X. F., Li, Q. K. et al., Seasonal patterns and environmental control of ecosystem respiration in subtropical and temperate forests in China, Science in China, Series D, 2005, 48(Supp. I): 93—105.
88. Sha, L. Q., Zhen, Z., Tang, J. W. et al., Soil Respiration in a Tropical Seasonal Rain Forest in Xishuangbanna, SW China, Science in China, Series D, 2005, 48(Supp. I). 189—197.
89. Zhou, C. Y., Zhou, G. Y., Wang, Y. S. et al., CO_2 efflux from different forest soils and impact factors in Dinghu Mountain, China, Science in China, Series D, 2005, 48(Supp. I): 198—206
90. Cao, M. K., Yu, G. R., Liu, J. Y. et al., Multi-scale observation and cross-scale mechanistic modeling on terrestrial ecosystem carbon cycle, Science in China, Series D, 2005, 48(Supp. I): 17—32.
91. Wang, Q. F., Niu, D., Yu, G. R. et al., Simulating the exchanges of carbon dioxide, water vapor and heat over Changbai Mountains temperate broad-leaved Korean pine forest ecosystem, Science in China, Series D, 2005, 48(Supp. I): 148—159
92. Ren, C. Y., Yu, G-R., Wang, Q. F. et al., Photosynthesis-transpiration coupling model at canopy scale in terrestrial ecosystem, Science in China, Series D, 2005, 48(Supp. I): 160—171.
93. Zhang, Y. Q., Yu, Q., Liu, C. M. et al., Simulation of CO_2 and latent heat fluxes in the North China Plain, Science in China, Series D, 2005, 48(Supp. I): 172—181.
94. Yakir, D., Sternber, L. D. S. L., The use of stable isotopes to study ecosystem gas exchange, Oecologia, 2000, 123: 297—311.
95. Battle, M., Bender, M. L., Tans, P. P. et al., Global carbon sinks and their variability inferred from atmospheric O_2 and $\delta^{13}C$, Science, 2000, 287: 2467—2470.
96. Bowling, D. R., Tans, P. P., Monson, R. K., Partitioning net ecosystem carbon exchange with isotopic fluxes of CO_2, Global Change Biology, 2001, 7: 127—145.