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A comparison of CO_2 fluxes via eddy covariance measurements with model predictions in a dominant subtropical forest ecosystem

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Abstract

CO_2 fluxes were measured continuously for twelve months (2003) using eddy covariance technique at canopy layer in a dominant subtropical forest in South China. Our results showed that daytime maximum CO_2 fluxes of the whole ecosystem varied from −15 to −20 μmol m^{-2} s^{-1}. The peaks of CO_2 fluxes appeared earlier than the peaks of solar radiation. Contribution of CO_2 fluxes in a subtropical forest in the dry season was 53% of the annual total from the whole forest ecosystem. Daytime CO_2 fluxes were very large in October, November and December, which was therefore an important stage for uptake of CO_2 by the forest ecosystem from the atmosphere.

Using the estimates of biomass, soil carbon and parameters of leaf photosynthesis from other studies at the same forest, we ran a process-based model, CBM (stands for CSIRO Biosphere Model) for this site, and compared the predicted fluxes of CO_2 with measurements. We obtained reasonable agreement. The mean difference between the simulated and measured daytime CO_2 fluxes from the year-round (8249 records) was −0.2 μmol m^{-2} s^{-1} and implied well within measurement accuracy.

Based on estimates of forest ecosystem respiration, NEE was calculated −242 and −276 gCm^{-2} year^{-1} for measured and modelled, respectively. In previous study, NPP for this forest stand was 694 gCm^{-2} year^{-1} during 2003/04 and litterfall was 424 gCm^{-2} year^{-1}. We therefore calculated NEE as −270 gCm^{-2} year^{-1} and very similar to the values obtained by measured and modelled CO_2 fluxes in this study.

1 Introduction

A recent study using biomass inventory data from China suggests that all forests in China are weak carbon sources, with an emission rate of 0.022 Pg C year^{-1}. Natural forests in China are estimated to be small carbon sinks, with 0.1 Pg C during the past decade (Fang et al., 2001). Research conducted during the last few years however, indicate that subtropical forests play a major role in CO_2 uptake due to their mature vegetation surfaces and also because of their evergreen nature (Zhou et al., 2006; Yan et al., 2006).

CO_2 is a major constituent of the greenhouse gases and its concentration in the atmosphere is directly influenced by human activities (Rannik et al., 2002), with significant impact on global climate. Recent studies have confirmed the important role played by terrestrial vegetation in the current global climate change, particularly, the role of forests in the global carbon cycle (GCN, 1995). Thus, ecologists have an important role in evaluating CO_2 fluxes from terrestrial ecosystems. Previous studies have relied on chamber techniques or cuvettes to evaluate leaf-level or ecosystem level CO_2 exchange processes of vegetation communities (Edwards and Sollins, 1973; Keller et al., 1986). However, such techniques are inherently limited, since they alter the local environment (Dennis et al., 1988). Of course, it is impossible to employ chambers for observing net CO_2 fluxes from forest canopy and long-term, continuous measurements to obtain statistically reliable results. Eddy covariance provides an alternative means for measuring CO_2 fluxes between the biosphere and the atmosphere. It is a non-invasive and non-destructive micrometeorological method which reveals continuous integrated signals with low spatial (typically 0.05 to 1 km^2) but high time resolution (usually 0.5 h). Gas exchange is measured at ecosystem or even landscape scale. It is a sound way to evaluate CO_2 uptake by the forest. Most of the flux towers have been established in North America, Europe and a few in Australia, Japan and South Korea. Tower measurements of CO_2 fluxes over the dominant subtropical forest have been made since 2002 in South China by direct eddy covariance method within the Chinaflux network. Understanding the gas-exchange processes between the vegetations and the atmosphere is extremely important in global biogeochemical cycles and also in predicting future climate change.

China's subtropical zone has unique features, which include: (1) humid and warm climate, contrary to other regions at the same latitude around the globe that are extremely arid. (2) Long disturbance history, with intensive human activity in large areas that have left almost no mature forest. (3) The most rapid industrialization in China

during the past 20 years, especially in the southern part of the country, but accompanied by the creation of large areas of young forest or rapid conversion of bare land in mountainous areas into forest. (4) Presence of evergreen broad-leaved forest, which must differ significantly from other forests in terms of the carbon cycle. Considerable uncertainties, however, exist regarding the carbon budget in the subtropical forests of Southern China despite several previous studies of the country's forest carbon budgets using forest inventory data (Fang and Chen, 2001; Wang et al., 2001) and process - based models (Cao et al., 2003).

Dinghushan ecological station was established as a part of the Network of Biosphere Reserve organized by UNESCO in 1970's. Since then measurements of microclimate, biomass, water balance, nutrient cycle etc., have been carried out continuously. Of great significance is the location of the site within a subtropical region, characterized by the above-mentioned features. The forests have been perfectly preserved in its original form from the Buddhism and local geomantic tradition, which regard them as holy sites and the monsoon forest is a dominated by subtropical forest and have become ideal research hot spots. Such regions of environmental transition are more sensitive to global climate change and the use of Eddy covariance technique could provide valuable net CO_2 flux data for assessing the role of these forests in the global CO_2 budget, i.e. whether they are a sink or source of carbon. We provide preliminary results from measurements and modeling for this site.

The objectives of the study were 1) estimate net CO_2 fluxes in a dominant subtropical forest ecosystem in Southern China, 2) develop a process-based model, CSIRO Biosphere Model (CBM), for long-term measurement of forest CO_2 fluxes, 3) compare measured net CO_2 fluxes using eddy covariance technique with model predictions and 4) determine the forest's role in regional CO_2 budget.

2 Materials and methods

2.1 Site descriptions

The study was carried out between January and December 2003 in the Dinghushan Biosphere Reserve located in Central Guangdong Province, South China, between 23°09′21″ and 23°11′30″ N and 112°30′39″ and 112°33′41″ E. The total area of the reserve is 1156 ha. Most of the Dinghushan area is coved with rolling hills and low mountains, with an altitude ranging from 100 to 700 m; Jilongshan is the highest peak with an elevation of 1000 m. The Dinghushan Biosphere Reserve has a typical subtropical monsoon humid climate, with an average annual temperature of 20.9°C. The highest and lowest monthly mean temperatures are 28.0°C in July and 12.0°C in January, respectively. the highest and lowest extreme temperatures recorded are 38.0°C and −0.2°C, respectively. The average annual rainfall is 1956 mm, of which more than 80% falls during the wet season (April–September) and less than 20% falls during the dry season (October–March). Annual mean relative humidity is 82%. The rock formations of Dinghushan are composed of sandstone and shale belonging to the Devonian Period. The predominant soil type is lateritic red earth at elevations of 400–500 m, followed by yellow earth, which is found at elevations of 500–800 m. Soil pH ranges between 4.5–6.0 and a rich humus layer is common. The Biosphere Reserve is a mature forest (subtropical monsoon evergreen broad-leaved forest), as well as its prophase succession communities (coniferous Masson pine forest and coniferous and broadleaved mixed forest). The age of the stand of the monsoon evergreen broadleaved forest examined in the present study is more than 400 yr, dominated by *Ca. chinensis*, *S. superba*, *Cr. chinensis*, *Cryptocarya concinna*, and *Machilus chinensis*. The flora includes 260 families, 864 genera, and 1740 species of wild plants.

2.2 CO_2 flux measurements

CO_2 flux was measured at the top of a 38 m-tall tower using the eddy covariance technique. The open-path technique was applied to eddy covariance measurement, which was set up at the height of 27 m (5th layer) Wind speed and temperature were measured with a sonic anemometer (CSAT3, Campbell), and CO_2/H_2O were measured with an open-path CO_2/H_2O analyzer (Li7500, Li-cor). The signals from the sensors were sampled at 10 Hz, and directly recorded with SDM technique by a data logger (CR5000, Campbell). CO_2 flux was calculated using the covariance of vertical wind velocity and the mixed ratio of fluxes for every 30 min. The three-dimensional coordinate rotation of wind velocity component was applied to set mean vertical on zero (w=0). The data of fluctuation in CO_2 concentration were detracted by linear least squares fitting to remove diurnal variation.

Meteorological data were also collected at seven layers aboveground, five layers underground. Solar radiation was measured at the top of the tower (CM11, CNR1, Kipp&Zonen). Rainfall was measured at the top of the tower (52203, R. M. Young). PAR (Photosynthetic photon flux density) was measure with sensors Li190SB (Li-cor) and LQS70-10 (Apogee). Temperature, humidity (HMP45C, Campbell and IRTS-P, Apogee), wind velocity (A100R, Vector) and wind direction (W200P, Vector) were measured on every layer aboveground. Soil temperature (105-T and 107-L, Campbell) and soil moisture (CS616, Campbell) were measured at every layer underground. All these routine meteorological signals were directly recorded with the data loggers (3 CR10X and 1 CR23X, Campbell). All recorded data were 30 min mean values.

2.3 Physiologically-based process model

The procedure of gap filling as well as the method for calculating ecosystem CO_2 fluxes were carried out as described by Wang and Leuning (1998) and Wang et al. (2001). We use CSIRO Biosphere Model (CBM) to predict the net fluxes of CO_2, H_2O and sensible heat. CBM consists of the two-leaf canopy model (Wang and Leuning, 1998; Wang et al., 2001) and soil scheme (Kowalczyk et al., 1994). The two-leaf canopy model calculates the net fluxes of CO_2, H_2O and sensible heat for the sunlit and shaded leaves separately, soil evaporation and sensible and ground heat fluxes. The soil scheme calculates soil temperature by integration the heat and water transfer equations for each of six vertical soil layers.

CBM requires inputs of site location (latitude), vegetation and soil types. The default values of vegetation parameters were taken from Sellers et al. (1994). Values of soil physical properties as provided by Clapp and Hornberger (1978) were used as default. In this study, we estimated most of vegetation and soil parameters from the past studies carried at the site (Table 1).

The turnover rate of leaf (τ_{leaf}), woody tissue (stem, braches and twigs) (τ_{wood}) and root (τ_{root}) were assumed to be 1.0, 0.03 and 0.14 year^{-1}, respectively. Soil carbon is divided into three pools: microbial biomass, fast and slow pools. We assumed that the turnover rates of microbial biomass (τ_{mb}), fast (τ_{fast})and slow (τ_{slow}) pools were 2.0, 0.5 and 0.004 year^{-1}, respectively. Respiration rates of plant tissue (r_{leaf}, r_{wood}, r_{root}) were calculated as

$$r_{\text{leaf}} = 0.015 v_{\text{cmax}}(T_{\text{leaf}})$$

$$r_{\text{wood}} = c_1 \tau_{\text{wood}} C_{\text{wood}} \exp(0.069 T_{\text{air}})/c_T$$

$$r_{\text{root}} = c_1 \tau_{\text{root}} C_{\text{root}} \exp(0.069 T_{\text{air}})/c_T$$

where C_{wood} and C_{root} are the amount of carbon in wood and roots (g m^{-2}), respectively. c_1 is an empirical scaling factor and was taken as 1.0 (dimensionless) and c_T is the number of seconds in a year (=31536000). Soil respiration, r_{soil}, is calculated as

$$r_{\text{soil}} = c_2 f_1(T_{\text{soil}}) f_2(\theta_{\text{soil}})(\tau_{\text{mb}} C_{\text{mb}} + \tau_{\text{fast}} C_{\text{fast}} + \tau_{\text{slow}} C_{\text{slow}})/c_T$$

where f_1 and f_2 are two empirical functions describing the sensitivity of soil respiration to soil temperature (T_{soil}) and moisture (θ_{soil}), respectively. C_{mb}, C_{fast} and C_{slow} represent the amount of carbon in microbial biomass, fast and slow pools (g m^{-2}), respectively. Parameter c_2 is a scaling factor, and is taken as 1.0.

3 Results

3.1 Gap filling and meteorological data

Gaps in long-term meteorological data observations inevitably occur due to instrument failure or to adverse others conditions. For our twelve-month (2003) observations, measurements were conducted efficiently, with meteorological data gaps occurring for only <1% of the time. Gaps were filled using linear interpolation for these short gaps by using data between adjacent above and below gaps. The daily meteorological data were calculated using half an hour record and given in Fig. 1a (solar radiation, air temperature, water vapor pressure deficit (VPD) and wind speed measured at the 38 m height of the tower) and Fig. 1b (soil moisture, soil temperature at 5cm depth and precipitation). The daytime was defined all half an hour records of solar radiation $\geq 10\,\text{w m}^{-2}$. There are 20–25 half an hour records for daytime in a day throughout a year. During the observation period, the maximum daytime mean value of solar radiation was $591\,\text{w m}^{-2}$ (DOY 185) and annual mean air temperature during daytime was 21.0°C. The maximum daytime mean value of VPD was 3.1 kPa (DOY 226) and yearly variations in the range 0.51–3.1 kPa. Wind speed was generally no more than $4\,\text{m s}^{-1}$ and an average annual value during daytime was $2.3\,\text{m s}^{-1}$.

3.2 Gap filling and CO fluxes data

To ensure data quality, CO_2 fluxes were edited manually to eliminate data due to obvious instrument failures or during rainfall when the open-path analyzer for CO_2 provides erroneous results. Satisfactory measurements were also obtained for CO_2 fluxes throughout the year, with 658 bad records <8% of 8249 records in total. For continuity of records, missing data for CO_2 fluxes were filled using relationships for CO_2 fluxes as a function of solar radiation, PAR, VPD and air temperature. We developed the procedure to maximize the correlations among these functions and found excellent agreement using a simple regression analysis of CO_2 fluxes as a function of PAR

(Fig. 2). CO_2 fluxes were dependent mainly on variation of PAR, which was also in line with previous study (Rannik et al., 2002). Figure 2a compared half an hour CO_2 fluxes records during daytime with the corresponding PAR data from 8–26 January and R^2=0.64 (n=352). We used this function to fill missing data for half hour records. The results were quite acceptable and a slight increase in R^2 (R^2=0.69, n=356) was obtained with a similar function of the mean PAR during daytime for the corresponding CO_2 fluxes from the gap-filled data in 2003 (Fig. 2b).

Half hourly records of CO_2 fluxes showed the typical fluctuations. Respective daytime CO_2 fluxes between 8–16 January and their mean values are shown in Fig. 3. CO_2 was transported from air layer above the flux-measurement height to forest canopy and the forest ecosystem was considered as a net sink of CO_2 during daytime. The maximum CO_2 uptake by forest occurred between 12:00 and 14:00, with a range of 15–20 μmol m^{-2} s^{-1}. The results were similar to previous studies in temperate deciduous broad-leaved forest and black spruce forest (Baldocchi and Vogel, 1996; Michael et al., 1997) and lower than a range of 18–27 μmol m^{-2} s^{-1} in boreal aspen forest (Black, 1996). The peaks of CO_2 fluxes appeared earlier than the peaks of solar radiation (Fig. 3). In such cases, the magnitude of CO_2 fluxes increased rapidly in the morning, but decreased gradually in the afternoon (Fig. 3). The similar results were found in a Brazilian rain forest and a tropical rain forest at Pasoh in Peninsular Malaysia (Grace et al., 1996; Yasuda et al., 2003).

Using all daytime mean values in each month, we calculated the monthly values of CO_2 fluxes, and applied them to further investigate seasonal variation in CO_2 fluxes as shown in Fig. 4. CO_2 fluxes in the dry season (October to March) were slightly higher than those in the wet season (April to September). Contribution of CO_2 fluxes in the dry season was 53% of the annual total. The daytime CO_2 fluxes were very large in October, November and December, which was therefore an important stage for uptake of CO_2 by the forest ecosystem from the atmosphere.

Estimates of some model parameters were listed in Table 1. CBM also requires inputs of half an hour records of meteorological data including solar radiation, PAR, air

temperature, soil temperature, relative humidity, VPD, wind speed and rainfall. We used the gap-filled meteorological data at the top layer of tower for running a process-based model, CSIRO Biosphere Model (CBM). Figure 5a presented measured and modelled the daytime CO_2 fluxes of half an hour records during DOY 140–158. The results of model simulation sounded well on half an hour scale for daytime CO_2 fluxes, but underestimated at noon and overestimated in the early morning and later afternoon. A comparison of the measured and simulated daytime CO_2 fluxes in 2003 was shown in Fig. 6a. The simulated daytime CO_2 fluxes with those of measured were relatively good (R^2=0.63 n=8249). Only at high values the model tends to underestimate CO_2 fluxes. The mean difference between the simulated and measured CO_2 fluxes from the year-round (8249 records) was -0.2 μmol m^{-2} s^{-1} and implied well within measurement accuracy. The model systematically overestimated the net CO_2 fluxes (i.e. the modelled net CO_2 fluxes were more negative). The previous study suggested that the measured CO_2 fluxes have random uncertainties from 10 to 20% because of stochastic natural turbulence (Rannik and Vesala, 1999).

Using half hourly records of the measured and simulated data, we calculated daytime mean values of CO_2 fluxes as shown in Fig. 5b. The mean daytime fluxes of the model performance in wet season were slightly higher than those of observations (see DOY 160–260), whereas for dry season, the CBM simulations were lower than those of measurements (see DOY 260–360). Although there was a relatively large scatter on half hourly scale (Fig. 6a), the correlation coefficient between the measured and simulated data was high for the mean daytime CO_2 fluxes and significant ($P<0.05$ n=365). Plot of the model simulations versus the measured values of the mean daytime CO_2 fluxes is shown in Fig. 6b. The model explained more than 68% of the variation in the mean daytime CO_2 fluxes in 2003.The monthly values of CO_2 fluxes (measured and modelled), PAR, based on the mean daytime values and rainfall monthly totals, are shown in Table 2.

4 Discussion

As stated in Table 2, both measured and modelled CO_2 fluxes showed that most of CO_2 uptake occurred during October–December, while least uptake occurred during February–March. In general, there is a strong positive correlation between CO_2 fluxes and PAR when PAR varies from zero to a potential maximum value (e.g. $2000\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) that the whole ecosystem saturates (Kimball et al., 1997; Winner et al., 2004). Therefore, the observed low CO_2 uptake observed during February–March could be attributed to lower PAR during this period, while a strong CO_2 uptake in October–December is attributed to high light intensities. The light-response of the whole ecosystem saturates at a light intensity of 600 to $800\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ (Fig. 2b) and $1000\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ (Fig. 2a) for the daytime mean values and the 30-min records, respectively, which is higher than the saturation photon flux density (400–$600\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) of individual leaves of the dominant tree species in this forest (Sun, 1991). The peak of PAR occurred during July with a mean daily light intensity of $867\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$, which was higher than the saturation light intensity of the trees. This could be one of reasons why the strong stage of CO_2 uptake was not directly related to the higher monthly PAR.

Rainfall events have significant effects on CO_2 uptake by aggravating soil respiration and reducing plant photosynthesis (Davidson et al., 1998; Michael et al., 2002; Wright et al., 2005). Lots of rainfall events during the wet season could explain why this forest ecosystem acted as a relative weak carbon sink. Based on PAR and rainfall, we could explain why the strong stage of CO_2 uptake did not coincide with the wet season, though, over which PAR and air temperature was high.

We calculated daytime uptake is only during the day C uptake of $957\,\text{gCm}^{-2}\,\text{year}^{-1}$ and $991\,\text{gCm}^{-2}\,\text{year}^{-1}$ from measured and modelled results respectively. We however, unable to estimate the net ecosystem exchange (NEE) directly due to uncertainties associated with measurements during the nighttime. Almost all eddy covariance limitations occur at night when the air becomes stably stratified. Some of these are instrumental; others are meteorological (Massman and Lee, 2002). In our measurements, we found obvious failure records were 3775>40% of 9271 in total. Soil respirations were measured in 2003/04 and released $1001\,\text{gCm}^{-2}\,\text{year}^{-1}$ in this forest stand (Yan et al., 2006). Soil respirations were also relatively constant on a diurnal time scale because changes in soil moisture are very slow and there is no significant relation between soil moisture and temperature, which tend to behave erratically, so that their effects may tend to cancel each other (Yan et al., 2006). Therefore, we can assume soil respirations during nighttime was $501\,\text{gCm}^{-2}\,\text{year}^{-1}$ (a half of $1001\,\text{gCm}^{-2}\,\text{year}^{-1}$). Soil respirations were 65–80% of ecosystem respirations generally (Wang et al., 2004). The NEE was estimated −242 and $-276\,\text{gCm}^{-2}\,\text{year}^{-1}$ for measured and modelled, respectively, according to soil respirations accounting for 70% of ecosystem respirations ($715\,\text{gCm}^{-2}\,\text{year}^{-1}$, C released during nighttime was $712\,\text{gCm}^{-2}\,\text{year}^{-1}$ based on CBM outputs. Our results show higher rates of CO_2 fluxes than the range of −133 to $-254\,\text{gCm}^{-2}\,\text{year}^{-1}$ reported by Wang et al. (2004) for a pine forest and similar to NEE for a southern boreal aspen forest reported by Griffis et al. (2004). Fan et al. (1990) and Grace et al. (1996) evaluated the daily values of NEE in Amazonian tropical forests as about $-0.60\,\text{gCm}^{-2}$ per day calculated from a short-term measurement and $-0.54\,\text{gCm}^{-2}$ per day measured during a 44-day-observation. Moreover, Grace et al. (1996) and Yasuda (2003) obtained daily NEE in the Amazonian forest in the dry season as $-1.08\,\text{gCm}^{-2}$ per day and $-2.44\,\text{gCm}^{-2}$ per day in a tropical rain forest based on 7-day-measurement. NEE in this study was similar to the median value of the range reported in previous findings, although most of data originate from short-term estimates. The NPP for this forest stand was $694\,\text{gCm}^{-2}\,\text{year}^{-1}$ during 2003/04 estimated by Yan et al. (2006) and the litter fall was $424\,\text{gCm}^{-2}\,\text{year}^{-1}$. We therefore calculated the NEE was $270\,\text{gCm}^{-2}\,\text{year}^{-1}$ and very similar to the values obtained by CO_2 fluxes measured and modelled in this study. CBM sensitivity analysis has been executed in previous studies (Wang and Leuning, 1998; Wang, 2000; Wang et al., 2001). In this study, it was difficult to make a statistically accurate determination of the optimal parameter combinations. The two key parameters canopy leaf area index (L)

and maximum carboxylation rate (v_{cmax}) were constant throughout because of the high temperature and evergreen nature of the forest ecosystem. By tuning on these two key parameters in the model, L (Range 4.5–8.0) and v_{cmax} (18–28), no better results were obtained. We suspected that this behavior was likely to be the result of CBM using constant vegetation parameters and fitted very well to simulate CO_2 fluxes for evergreen forests in the tropical and subtropical regions.

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Table 1. Estimates of vegetation and soil properties from past studies at Dinghushan Station.

Parameter	Unit	Estimate	Source
Canopy leaf area index	$m^2\,m^{-2}$	6.5	Yan et al.
v_{cmax} at 20°C	$\mu mol\,m^{-2}\,s^{-1}$	23	Wen, DZ (unpublished)
j_{max} at 20°C	$\mu mol\,m^{-2}\,s^{-1}$	63	Wen, DZ (unpublished)
Canopy height	m	18	This study
Leaf carbon	$g\,m^{-2}$	293	Tang et al. (2005)
Woody carbon	$g\,m^{-2}$	9315	Tang et al. (2005)
Root Carbon	$g\,m^{-2}$	2142	Tang et al. (2005)
Soil carbon	$g\,m^{-2}$	8800	Yi et al. (2003)
Soil bulk density	$Mg\,m^{-3}$	1.21	Zhang and Zhuo (1985)
Soil water wilting point	fraction	0.114	Zhang and Zhuo (1985)
Soil water field capacity	fraction	0.346	Yan et al. (2000)
Soil clay:sand:silt fraction	proportion	0.32:0.20:0.48	Zhang and Zhuo (1985)
Hydrological conductivity at saturation	$m\,s^{-1}$	8.45e-5	Zhang and Zhuo (1985)
Suction at saturation	m	0.63	Zhang and Zhuo (1985)

Table 2. Monthly averages for daytime CO_2 fluxes (measured and modelled) and PAR. Rainfall was calculated the total during 24-h in each month.

Month	CO_2 flux Measured	Stand deviation	CO_2 flux Modelled	Stand deviation	PAR	Stand deviation	rainfall
Jan	−5.75	1.60	−4.82	1.13	493.46	23.78	28.00
Feb	−3.46	0.83	−3.94	0.96	321.91	21.92	26.70
Mar	−4.04	1.43	−3.91	1.29	297.40	20.00	91.60
Apr	−5.12	2.05	−5.07	1.68	413.73	25.81	91.10
May	−5.31	1.12	−6.25	0.41	544.66	23.79	52.10
Jan	−4.81	1.19	−5.52	1.01	501.35	24.12	287.60
Jul	−4.68	0.83	−6.07	0.80	866.57	24.49	91.90
Aug	−4.93	0.47	−6.02	0.35	647.66	21.60	321.80
Sep	−5.72	1.17	−5.88	1.03	618.51	26.42	305.70
Oct	−7.20	1.17	−7.00	0.44	674.78	19.90	11.40
Nov	−6.74	1.07	−6.23	0.73	547.09	20.65	0.00
Dec	−6.98	0.32	−6.31	0.96	583.80	13.61	0.10
Mean	−5.40	1.10	−5.58	0.82	542.58	22.18	–

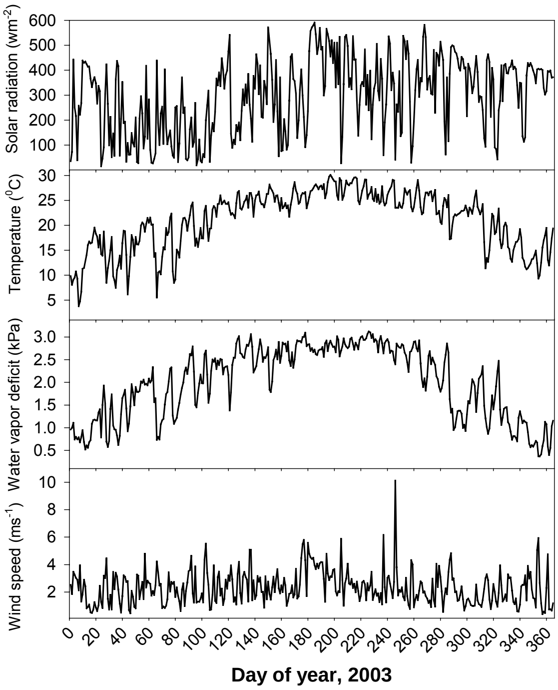

Fig. 1a. Variations of daytime mean values in solar radiation, air temperature, VPD (water vapor deficit) and wind speed at 38 m height in 2003.

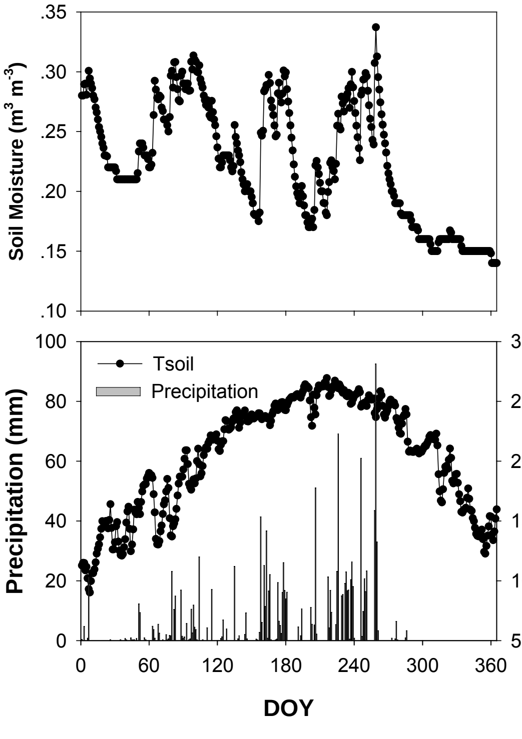

Fig. 1b. Variations of daily mean soil moisture, soil temperature at 5cm depth and daily precipitation.

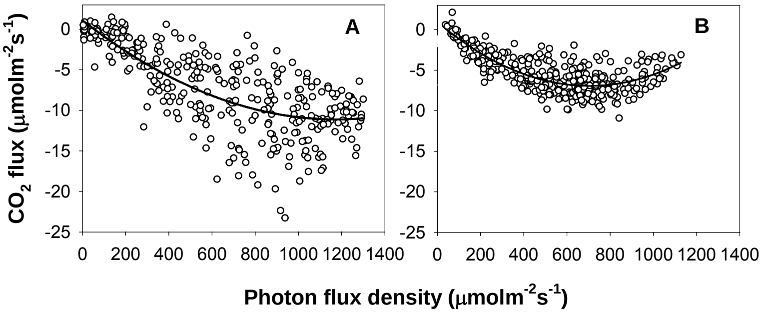

Fig. 2. Response of daytime CO_2 fluxes to photon flux density. **(A)** was half-hour records during daytime with the corresponding photon flux density data from 8–26 January; **(B)** was the mean daytime CO_2 fluxes with the corresponding photon flux density data in 2003.

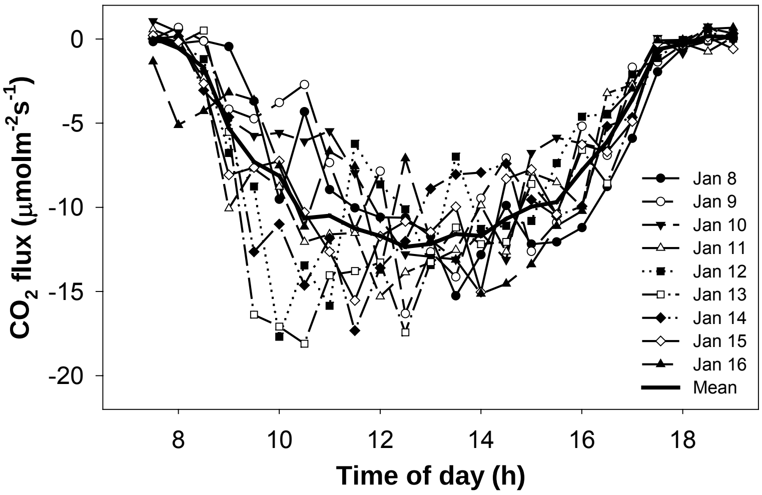

Fig. 3. Variations in half an hour records of CO_2 fluxes during daytime on 8–16 January and their mean values with the dashed line.

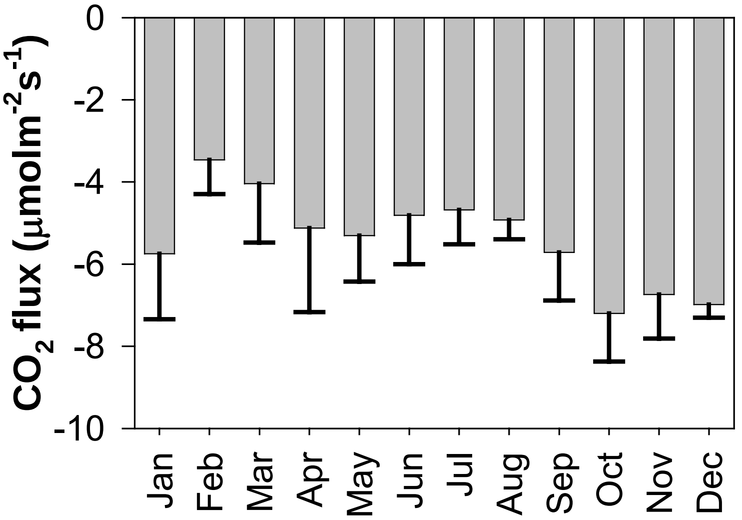

Fig. 4. Variations in eddy covariance measurements of monthly CO_2 fluxes and their SD.

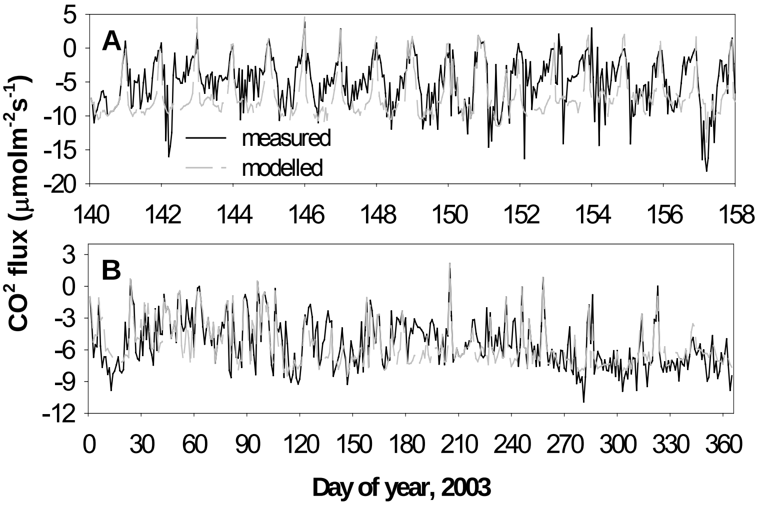

Fig. 5. Comparison of eddy covariance measurements and CBM outputs. **(A)** showed half an hour records during DOY 140–158; **(B)** showed the mean daytime CO_2 fluxes in 2003.

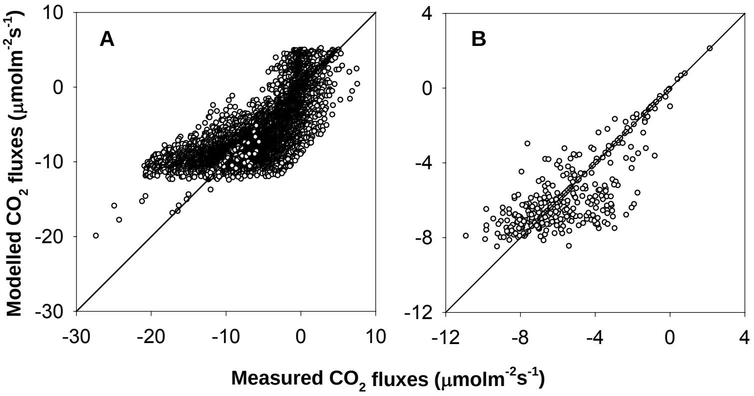

Fig. 6. Comparison between modelled and measured CO_2 fluxes for 2003. The dashed lines were 1:1 correspondence lines. **(A)** was measured and simulated half and hour records for CO_2 fluxes in 2003 and; **(B)** was measured and simulated daytime mean of CO_2 fluxes in 2003.