Postprint: Variation Characteristics of CO2 Concentration and Flux in the Coniferous-Broadleaf Mixed Forest at Dinghushan

Authors: Huang Jun, Mai Boru, Deng Xuejiao, Xiao Wei, Xiao Wei, Shen Ziqi, Xiao Wei

Date: 2018-05-16T00:00:00+00:00

Abstract

This study utilizes 2012 CO2 flux and meteorological data from the Dinghushan subtropical evergreen broad-leaved forest flux observation station, a typical forest vegetation ecosystem in the Pearl River Delta, to analyze the variation characteristics of CO2 flux, net ecosystem CO2 exchange (NEE), and CO2 concentration, as well as their relationships with meteorological factors, providing a reference basis for the evaluation and research of carbon sources/sinks and carbon cycling in the Pearl River Delta region. The results show that: (1) The diurnal variation of CO2 concentration exhibits a "one-peak-one-valley" pattern, with maximum values occurring at night or around sunrise and minimum values in the afternoon; the diurnal variation of CO2 flux shows a "single-valley" curve, reaching its minimum value (negative) around midday during daytime, and being relatively high (positive) at night and in the morning. (2) The seasonal average values of CO2 flux follow the order of spring > summer > winter > autumn, while the seasonal average values of CO2 concentration follow the order of winter > spring > autumn > summer, i.e., higher in the non-growing season than in the growing season, which may be related to changes in CO2 source/sink intensity caused by seasonal variations in plant phenology. (3) In 2012, the annual average CO2 concentration of the Dinghushan forest ecosystem was 664.7 mg · m-3, the annual average CO2 flux was -0.079 mg · m-2 · s-1, and the NEE was -611 gC · m-2 · a-1, indicating that the Dinghushan coniferous and broad-leaved mixed forest has been in a rapid growth phase in recent years and possesses a strong carbon sink function. (4) Both CO2 flux and concentration show significant negative correlations with air temperature and vapor pressure deficit, with the correlation between CO2 concentration and air temperature being the strongest, followed by that with vapor pressure deficit, indicating that air temperature and vapor pressure deficit are key meteorological factors affecting CO2 concentration and flux. Influenced by human activities and climate change, this study finds that the carbon sink function of the Dinghushan forest ecosystem has been enhanced in recent years.

Full Text

Characteristics of CO2 Concentration and Flux Variations in the Mixed Conifer-Broadleaf Forest at Dinghu Mountain

HUANG Jun[1],[2], MAI Boru[3], DENG Xuejiao[3], XIAO Wei[1]*, WANG Chunlin[2], SHEN Ziqi[2]
[1]Yale-NUIST Center on Atmospheric Environment, Nanjing University of Information Science and Technology, Nanjing 210044, China
[2]Guangzhou Climate and Agrometeorology Center, Guangzhou 511430, China
[3]Guangzhou Institute of Tropical and Marine Meteorology, CMA, Guangzhou 510080, China

DOI: 10.11931/guihaia.gxzw201803028

Abstract

This study analyzes the variation characteristics of CO2 flux, net ecosystem CO2 exchange (NEE), and CO2 concentration, along with their relationships with meteorological factors, using CO2 flux and meteorological data from 2012 collected at the Dinghu Mountain flux observation station in a typical forest vegetation ecosystem of the Pearl River Delta. The results provide a reference for evaluating carbon sources, sinks, and cycling in the Pearl River Delta region. The findings indicate: (1) Diurnal variation of CO2 concentration follows a "single-peak, single-valley" pattern, with maximum values occurring at night or around sunrise and minimum values in the afternoon. CO2 flux exhibits a "single-valley" curve, reaching minimum values (negative) around midday and higher values (positive) at night and in the morning. (2) The seasonal average of CO2 flux follows the order: spring > summer > winter > autumn, while the seasonal average of CO2 concentration follows: winter > spring > autumn > summer, indicating higher concentrations in the non-growing season than in the growing season, likely related to seasonal changes in CO2 source-sink intensity caused by plant phenology. (3) In 2012, the annual mean CO2 concentration in the Dinghu Mountain forest ecosystem was 664.7 mg · m ^{3}, the annual mean CO2 flux was -0.079 mg · m ^{2} · s ^{1}, and NEE was -611 gC · m ^{2} · a ^{1}, demonstrating that the mixed conifer-broadleaf forest at Dinghu Mountain has been in a rapid growth phase in recent years with strong carbon sink function. (4) Both CO2 flux and concentration show significant negative correlations with air temperature and vapor pressure deficit, with temperature showing the highest correlation, followed by vapor pressure deficit, indicating these are key meteorological factors affecting CO2 concentration and flux. Influenced by human activities and climate change, this study finds that the carbon sink function of the Dinghu Mountain forest ecosystem has been enhanced in recent years.

Keywords: mixed conifer-broadleaf forest, CO2 flux, eddy covariance method, Dinghu Mountain

Introduction

Carbon dioxide (CO2) is the most important greenhouse gas in the global atmosphere, with its concentration increasing at an average rate of 2 ppm per year and contributing up to 60% of global warming (Nisbet & Myers et al., 2007; Prentice et al., 2011; Diao et al., 2015). Forests cover approximately 40% of the land surface and represent the most extensive and complex terrestrial ecosystems. With their unique ecological structure and function, forests exchange CO2 frequently with the atmosphere, accounting for over 90% of terrestrial ecosystem carbon exchange and storing approximately three times the amount of carbon found in the atmosphere (Rollinger et al., 1998). Plants absorb atmospheric CO2 through photosynthesis and store it long-term in the ecosystem, while simultaneously releasing CO2 through respiration, soil microbial respiration, and decomposition of litter (Nisbet & Myers et al., 2007; Wofsy et al., 1993; Wu et al., 2003). Understanding the variation characteristics of CO2 flux and concentration in forest ecosystems is therefore crucial for assessing forest carbon cycling, carbon source-sink characteristics, and climate change.

In recent years, numerous studies on CO2 concentration and flux have been conducted in China, with the eddy covariance system being widely applied to investigate CO2 variation patterns (Zhang et al., 2010). Zhang et al. (2012) studied the characteristics and influencing factors of net ecosystem CO2 flux in grasslands, finding that NEE during the growing season is primarily affected by temperature. Chen et al. (2016) used seven-layer CO2 observations and eddy covariance systems to conduct long-term observations and research on CO2 concentration and flux in a subtropical bamboo forest in Anji during the growing season. Xu et al. (2016) investigated the seasonal variation characteristics of CO2 flux and related environmental factors in Haizhu Lake Wetland Park in Guangzhou using static chamber-gas chromatography methods. Peng et al. (2017) and Xu et al. (2018) used the eddy covariance method to observe CO2 flux during the growing season in a typical poplar forest in the Dajiuhu Peat Wetland and Hongze Lake Wetland, respectively, comparing variation characteristics and influencing factors between growing and non-growing seasons, and found that water level changes in Hongze Lake Wetland could alter carbon sink function by affecting soil moisture. Additionally, with the development of remote sensing technology, satellite-based methods can be used to study the spatiotemporal variation characteristics of CO2 concentration and flux in forest ecosystems, and combined with ground-based observations, can further improve the accuracy of CO2 source-sink assessments (Saeki et al., 2009; Bu et al., 2015;

Bu et al., 2015).

The Pearl River Delta (PRD) region features a diverse, comprehensive, and complex ecosystem (Mai et al., 2014) that includes South Asian subtropical forests, green spaces, grasslands, and farmland. As one of China’ s most economically developed regions, the PRD has experienced rapid increases in greenhouse gas emissions with distinct regional characteristics due to rapid industrialization and urbanization (Deng et al., 2006). In recent years, research on CO2 flux in different ecosystems of the PRD has gradually expanded, yielding some preliminary results that reveal inconsistent patterns of CO2 concentration and flux variation and their responses to meteorological factors across different regions and vegetation types (Zhang et al., 2002; Yan et al., 2003; Zhou et al., 2004; Wang et al., 2006, 2007). Influenced by urban development and climate change, CO2 concentration, flux, and carbon sequestration benefits of forest ecosystems also change. However, research on CO2 flux in forest ecosystems, especially South Asian subtropical forest ecosystems, and their relationships with meteorological factors has been relatively limited in recent years. South Asian subtropical forest ecosystems possess rich species diversity and complex community structures, playing an important regulatory role in regional ecosystem carbon balance (Zhou et al., 2003), making carbon source-sink assessment of these forests a research hotspot. The mixed conifer-broadleaf forest at Dinghu Mountain represents a typical South Asian subtropical evergreen broad-leaved forest in the PRD region and is one of the most characteristic and valuable research areas in the South Asian subtropical zone (Zhang et al., 2002).

This study uses data from 2012 collected at the Dinghu Mountain flux observation station in the PRD forest ecosystem to analyze variation characteristics of CO2 flux and concentration, compare with previous research findings, and identify key meteorological factors influencing these variations, providing a reference for carbon source-sink and carbon cycling research in the PRD region.

1.1 Study Area Overview

The Dinghu Mountain Nature Reserve is located in Zhaoqing City, Guangdong Province (112°30 -112°33 E, 23°09 -23°11 N), characterized by hills and low mountains with elevations ranging from 14 to 1,000 m. The vegetation represents relatively rich South Asian subtropical zonal vegetation along the Tropic of Cancer, typical of South Asian subtropical evergreen broad-leaved forests dominated by *Castanopsis chinensis*, *Schima superba*, and *Cryptocarya chinensis* communities (Wang et al., 2006). The soil in the monsoon evergreen broad-leaved forest sample plot is lateritic red soil with a pH of 3.86, thickness of 60-90 cm, ground litter layer thickness of 1-3 cm, and coverage of 80%-90%. The climate is classified as South Asian subtropical monsoon humid type, with a dry season from October to March and a wet season from April to September. The area enjoys abundant climatic resources of light, heat, and water: annual solar radiation of approximately 4,665 $\mathrm{MJ} \cdot \mathrm{m}^{2} \cdot \mathrm{a}^{1}$, mean annual sunshine duration of 1,433 h, mean annual temperature of 21.0 °C (minimum of 12.0 °C in

January and maximum of 28.0 °C in July), mean annual relative humidity of 82%, and mean annual precipitation of 1,956 mm, with 76% of rainfall concentrated in April–September (Wang et al., 2007).

1.2 Data Observation and Processing

The Dinghu Mountain South Asian subtropical evergreen broad-leaved forest flux observation station is installed in a mixed conifer-broadleaf forest at an altitude of 240 m in the core area of the Dinghu Mountain Nature Reserve and is a member of the Chinese Academy of Sciences Flux Network (ChinaFLUX). The eddy covariance observation system is installed on the fifth platform of the flux observation tower at a height of 27 m, consisting primarily of a three-dimensional ultrasonic anemometer-thermometer (CSAT3, Campbell Inc., USA) and an open-path CO /H O analyzer (Li-7500, Li-Cor Inc., USA). The data logger (CR3000, Campbell Inc., USA) has an original sampling frequency of 10 Hz and calculates and stores 30-minute average CO flux (Fc) and friction velocity (u*) data online according to the eddy covariance method. During online calculation, the software automatically applies corrections for virtual temperature and air density variations (Webb et al., 1980; Schotanus et al., 1983). Conventional meteorological observations including air temperature, wind speed, precipitation, and relative humidity are collected and recorded as 30-minute averages by a CR10X-TD data logger. The observation period for this study is 2012, during which the flux equipment underwent zero and span calibration. Due to equipment failure, conventional meteorological data were missing for March-April, and flux data were missing for November.

The 30-minute average flux and meteorological data from 2012 were matched for temporal consistency. Additionally, data quality control was required to exclude abnormal and missing data caused by equipment failure, rainfall, and atmospheric motion. Thirty-minute records meeting any of the following conditions were rejected: (1) simultaneous rainfall occurrence; (2) insufficient atmospheric turbulence with friction velocity u* below 0.2 m · s^{1}; (3) CO flux outside the valid range of −2.0 to 2.0 mg · m^{2} · s^{1}, CO concentration outside 500–800 mg · m^{3}, or water vapor concentration outside 0–40 g · m^{3} (Sun et al., 2012); (4) obviously anomalous outliers.

1.3 Research Methods

The eddy covariance method is a technique for directly calculating turbulent transport quantities (turbulent fluxes) from pulsation observations, also known as the turbulent pulsation method (Baldocchi et al., 1988). The CO flux calculation formula can be expressed as:

[Equation would appear here]

where w represents the instantaneous deviation (perturbation) of vertical wind speed from its mean value, c is the instantaneous perturbation of CO density in air, and is the covariance of instantaneous vertical wind speed and CO density (Jia et al., 2010; He et al., 2006). The eddy covariance method is the most direct measurement technique, capable of stably monitoring pulsation values at 10 Hz and online calculation of their covariances (He, 2006), and has become the primary observation technique for the international flux observation network (FLUXNET) (Baldocchi & Vogel, 1996). Application of this formula requires several assumptions (Wang et al., 2007): (1) quasi-steady atmospheric turbulence; (2) horizontally uniform mixing (advection negligible); (3) existence of a constant flux layer near the surface; (4) all eddies affecting fluxes are measured; (5) the flux measured by the equipment represents the flux from the underlying surface at the observation location.

Vapor Pressure Deficit (VPD) refers to the difference between saturated vapor pressure and actual vapor pressure at a given air temperature (Rogers et al., 1996) and is one of the important driving factors of vegetation evapotranspiration and one of the most important climatic factors for simulating plant water and carbon fluxes in ecological models (Zhang et al., 2014). VPD affects the closure of plant leaf stomata, thereby controlling physiological processes such as plant transpiration and photosynthesis (Jarvis et al., 1976), which in turn influence plant growth and development. VPD can be estimated from atmospheric relative humidity (RH) and air temperature (T) (Richard et al., 1998). The calculation formula is:

[Equation would appear here]

Net Ecosystem Exchange (NEE) represents changes in ecosystem carbon storage caused by ecosystem photosynthesis, biological and non-biological respiration, or consumption of atmospheric CO (Garratt, 1975). NEE can be described by the following equation:

[Equation would appear here]

where Fc is the observed CO flux and Fs is the CO storage below the observation height. When u* is low, indicating weak atmospheric turbulence in the vertical direction, most CO is stored in the air, resulting in larger Fs; when u* is high, indicating vigorous vertical atmospheric turbulence, the exchange capacity between plants and atmospheric CO increases, resulting in larger Fc (Sun et al., 2012). In NEE calculations, it is assumed that vertical atmospheric turbulence is sufficient and that advective flux and horizontal turbulent flux are negligible (Wofsy et al., 1993; Law et al., 1999).

Typically, Fs can be estimated using either multi-layer CO concentration changes or single-layer CO concentration change methods (Hollinger et al., 1994; Griffis et al., 2003). According to previous research, results calculated using the single-layer CO concentration change method are basically consistent with those measured using multi-layer methods (Aubinet et al., 2001; Yan et al., 2003; Sun et al., 2012), with minimal impact on annual NEE. Since this study only has single-layer observation data, Fs was estimated using the single-layer CO concentration change method according to Hollinger et al. (1994):

[Equation would appear here]

where Δz is the distance from the flux equipment to the ground (taken as 27 m), ΔC(z) is the change in CO concentration between two observations |[CO]t - CO |, and Δt is the time interval between two observations (taken as 1,800 s). Considering that the selected data are under conditions of sufficient turbulence (u* > 0.2 m $\cdot$ s^{1}), further quality control was applied to exclude data meeting the following conditions: Fs > 0.3 mg $\cdot$ m^{2} $\cdot$ s^{1}, |[CO]t - CO | > 20 mg $\cdot$ m^{3}, to reduce anomalous outliers (Sun et al., 2012).

In statistical analysis, daily, monthly, and annual means in this study are arithmetic averages of data within the corresponding time periods, and correlations between data are represented using Pearson correlation coefficients.

2.1 Annual Variation Characteristics of Meteorological Elements

The annual variation of meteorological elements at Dinghu Mountain in 2012 is shown in Figure 1 [Figure 1: see original paper]. The mean annual air temperature (T) was 19.9 °C, 1.1 °C lower than the historical average (Wang et al., 2016), with daily mean T ranging from 2.5 to 30 °C, peaking in August during summer and reaching minimum in January during winter. The mean annual relative humidity (RH) was 85%, 3% higher than the historical average (Yan et al., 2003), with daily mean RH ranging from 50 to 100%, remaining relatively humid throughout the year and reaching minimum in October during autumn. The mean annual VPD was 0.4 kPa, with daily mean VPD ranging from 0 to 1.4 kPa, maximum in August during summer, higher in spring and summer, and lower in autumn and winter. According to long-term statistics, the subtropical evergreen coniferous-broadleaf mixed forest at Dinghu Mountain has a rainy season from April to September and a dry season from October to March. In 2012, due to higher temperatures and vigorous vegetation growth during April-October, water consumption was greater, resulting in higher VPD during these months compared to the dry season. The mean annual wind speed (V) was 1.7 m $\cdot$ s^{1}, with daily mean V ranging from 0 to 5.8 m $\cdot$ s^{1}, maximum in July during summer. Influenced by topography, the prevailing wind directions throughout the year are northeasterly and southwesterly.

2.2 Overall Characteristics of Daily Variation in CO2 Flux and Concentration

Figure 2 [Figure 2: see original paper] shows the daily average variations of CO2 concentration, Fc, Fs, and NEE at Dinghu Mountain in 2012, where the upper "T" indicates daily maximum values, the lower "T" indicates daily minimum values, the middle solid black line represents daily averages, and vertical dashed lines are connecting lines. The results show that the daily mean Fc at the Dinghu Mountain forest ecosystem in 2012 ranged from −0.516 to 0.373 mg $\cdot$ m^{2} $\cdot$ s^{1}, with an annual mean of −0.079 mg $\cdot$ m^{2} $\cdot$ s^{1}; Fs ranged from −0.082 to 0.222

mg · m ^{2} · s ^{1}, with an annual mean of −0.004 mg · m ^{2} · s ^{1}; CO concentration ranged from 608.21 to 768.7 mg · m ^{3}, with an annual mean of 664.7 mg · m ^{3}; and NEE ranged from −1.183 to 0.368 mg · m ^{2} · s ^{1}, with an annual mean of −0.063 mg · m ^{2} · s ^{1}. Both annual mean Fc and NEE were negative, indicating that the forest ecosystem absorbed CO and functioned as a carbon sink throughout the year.

2.3 Diurnal Variation Characteristics of CO2 Concentration and Flux

Data from typical months in the four seasons of 2012 were selected for Fc, Fs, NEE, and CO concentration, and 30-minute data were averaged to obtain mean diurnal variations for different seasonal representative months, as shown in Figure 3 [Figure 3: see original paper]. The diurnal variation characteristics of Fc, Fs, and NEE in the representative months of the four seasons show clear and consistent patterns.

Fc, Fs, and NEE generally exhibit a "single-valley" curve, being higher and positive in the morning, evening, and nighttime with smaller variation amplitudes, and negative during daytime with larger variation amplitudes. The transition from positive to negative occurs between 7:00–9:00 in the morning, and from negative to positive between 17:00–19:00 in the evening (Figure 3). From 9:00 to 17:00 during daytime, values remain negative, reaching minimum (most negative) around 13:00 at noon. NEE is clearly controlled by photosynthetically active radiation; plants absorb CO through photosynthesis, and CO is transported downward from the atmosphere above the canopy through turbulent exchange, causing canopy CO concentration to decrease. Canopy Fc, Fs, and NEE are basically negative, and the ecosystem functions as a carbon sink, with larger variation amplitudes in autumn and winter and smaller amplitudes in spring and summer. From 18:00 to 08:00 the next day at night, values are basically positive. Influenced by turbulence, flux is negative during some periods. Additionally, due to weakened photosynthetically active radiation, plants cease photosynthesis and switch to respiration, releasing CO , while soil respiration also releases CO . Coupled with the stable temperature inversion that often occurs near the ground at night, CO gradually accumulates within the canopy and rises above the atmospheric CO concentration above the canopy. CO is slowly transported upward through atmospheric turbulent exchange, making Fc, Fs, and NEE predominantly positive. At night, with photosynthetically active radiation at zero, NEE equals total ecosystem respiration (Reco), and the ecosystem overall functions as a carbon source.

CO concentration diurnal variation generally follows a "single-peak, single-valley" pattern. The South Asian subtropical evergreen coniferous-broadleaf mixed forest at Dinghu Mountain shows maximum CO concentration at 7:00–8:00 in the morning, gradually decreasing after sunrise, reaching minimum at 16:00, and then gradually increasing again. This differs from the "single-peak" pattern of temperate deciduous broad-leaved forests (Jiao et al., 2011) and the "double-peak" pattern of Xishuangbanna tropical seasonal rainforests (Tan et al., 2008), indicating that diurnal variation characteristics of CO concentration differ among forests in different regions. Comparing different months, the diurnal variation characteristics of CO concentration in July show good consistency with Fc, with Fc decreasing as CO concentration decreases and increasing as CO concentration increases. In other months, CO concentration diurnal variation shows the opposite pattern to Fc, with CO concentration increasing when Fc decreases and decreasing when Fc increases.

The maximum daily downward Fc transport occurs around noon. In 2012, the average maximum Fc at Dinghu Mountain ranged from -0.5 to -0.68 mg · m^{2} · s^{1}. Compared with previous studies (Table 1), this is lower than northern poplar forests (Black et al., 1996), temperate deciduous broad-leaved forests (Baldocchi & Vogel, 1996), and temperate black spruce forests (Michael et al., 1997) during their growing seasons, but higher than northern pine forests (Baldocchi & Vogel, 1996) during their growing season, and similar to the evergreen coniferous-broadleaf mixed forest at Dinghu Mountain in 2003 (Wang et al., 2006) and subtropical artificial coniferous forests (Liu et al., 2004).

2.4 Seasonal Variation Characteristics of CO2 Flux and Concentration

The monthly average time series of Fc is shown in Figure 4 [Figure 4: see original paper]. Annual monthly mean Fc ranged from -0.15 to 0.017 mg · m^{2} · s^{1} (Figure 4a), with maximum monthly mean in April during spring and minimum in October during autumn. Most monthly Fc values at Dinghu Mountain forest ecosystem were below zero, except for April which showed a positive mean of 0.007 mg · m^{2} · s^{1}. Among monthly variations, September showed the largest amplitude and March the smallest. Seasonal mean Fc values were all negative, following the order: spring > summer > winter > autumn. The positive mean Fc in April may be related to the onset of the rainy season in South China, as precipitation statistics from the nearby Sihui National Basic Meteorological Station (20 km away) show April cumulative precipitation reached 379.5 mm, the maximum monthly value, and abundant precipitation may reduce photosynthetic efficiency.

The monthly average time series of Fs is shown in Figure 4b. Monthly mean Fs ranged from -0.011 to 0.003 mg · m^{2} · s^{1}, with maximum in July and minimum (largest negative) in October. Except for February and July which showed positive values, all other months were negative. Fs is not zero at the monthly scale, indicating that advective or drainage effects influence monthly Fs. February Fs of 0.0005 mg · m^{2} · s^{1} was closest to zero, indicating minimal influence from advection or drainage. The largest positive value in July and largest negative value in October may be due to strong vertical convection and horizontal wind speeds during these months, making the ecosystem prone to advective or drainage effects under strong turbulent exchange conditions. Therefore, Fs should be considered when estimating NEE at monthly time scales for forest ecosystems.

The monthly average time series of CO concentration is shown in Figure 4c. Annual monthly mean CO concentration ranged from 632.1 to 721.4 mg · m ^{3}, with maximum monthly mean in January during winter, followed by December, and minimum in August during summer. Among monthly variations, April showed the largest amplitude and March the smallest. CO concentration in the non-growing season was higher than in the growing season, related to plant growth seasons. With vigorous plant growth in summer, more atmospheric CO is absorbed, resulting in lower CO concentration in August. Higher CO concentration in winter may be related to reduced light and low temperatures inhibiting plant growth and weakening photosynthetic consumption of CO . Additionally, higher winter CO concentration may be influenced by combustion and pollution emissions from surrounding urban areas.

The monthly average time series of NEE is shown in Figure 4d. Monthly NEE ranged from −0.192 to −0.009 mg · m ^{2} · s ^{1}, with negative values in all months, indicating strongest carbon sequestration in September, October, and January, and weakest in April, demonstrating that the forest ecosystem is a strong carbon sink. The annual mean NEE at Dinghu Mountain in 2012 was −0.063 mg · m ^{2} · s ^{1}, which converts to −611 gC · m ^{2} · a ^{1} for comparison purposes. Table 4 compiles annual mean NEE values for typical ecosystems worldwide, showing that Dinghu Mountain' s annual mean NEE is higher than all reported forest ecosystems except for the artificial coniferous forest at Qianyanzhou (−645 gC · m ^{2} · a ^{1}) (Liu et al., 2004), and significantly higher than northern Chinese forests and North American forests, generally following the universal pattern of decreasing NEE with increasing latitude (Falge et al., 2001).

2.5 Meteorological Factors Influencing CO2 Concentration and Flux

Correlation analysis between Fc, Fs, NEE, CO concentration and meteorological elements across seasons is shown in Table 3 . Fc, Fs, NEE, and CO concentration are negatively correlated with air temperature and vapor pressure deficit, and positively correlated with relative humidity and horizontal wind speed. In summer, correlations of Fc, Fs, NEE, and CO concentration with temperature and vapor pressure deficit are higher than those with relative humidity and horizontal wind speed, indicating that temperature and vapor pressure deficit have greater influence on Fc, Fs, NEE, and CO concentration. Higher temperatures and larger vapor pressure deficits result in smaller Fc, Fs, and NEE values and stronger plant CO exchange.

The correlation between NEE and temperature is higher in summer and autumn than in winter and spring, indicating that during the summer half-year when photosynthesis is stronger, temperature has a greater effect on plant photosynthesis than on respiration, with higher temperatures enhancing photosynthesis. During the winter half-year when photosynthesis is weaker, temperature has a greater effect on plant respiration than on photosynthesis, with higher temperatures enhancing respiration. The correlation coefficient between NEE and VPD is negative throughout the year (−0.137), indicating that VPD has a greater impact on photosynthesis than on respiration, primarily because higher VPD increases plant stomatal conductance, making CO exchange between plants and the atmosphere more active (Sun et al., 2012).

CO concentration shows the highest correlation with temperature, with an annual correlation coefficient of −0.907, indicating that temperature is the key meteorological factor affecting CO concentration in South Asian subtropical evergreen broad-leaved forests. Increased temperature accelerates metabolism in plants and microorganisms, and when plant photosynthesis exceeds respiration, the forest ecosystem functions as a carbon sink, thereby reducing atmospheric CO concentration (Figure 5 [Figure 5: see original paper]).

3 Conclusions and Discussion

(1) CO concentration and Fc show clear diurnal variation characteristics. Fc, Fs, and NEE generally follow a “single-valley” curve, reaching minimum values (negative) around midday and higher values (positive) at night and in the morning. CO concentration follows a “single-peak, single-valley” pattern, with maximum values at night or around sunrise, decreasing after sunrise, reaching minimum in the afternoon, and gradually increasing again after sunset. Related studies indicate that under ideal conditions, ecosystems have no advective or drainage effects, and Fs during periods of weak nighttime turbulence would be balanced by plant photosynthesis after sunrise, so Fs should be zero at daily and longer timescales (Aubinet et al., 1999). Therefore, Fs can be ignored when calculating NEE at medium to long timescales (Lee, 1998; Wu et al., 2005). However, this study found that Fs is not zero at daily or annual timescales, indicating that advective or drainage effects exist in the Dinghu Mountain forest ecosystem at night, preventing the CO reduced during daytime from balancing the CO stored at night in the canopy layer (Zhang et al., 2010), resulting in non-zero Fs. Therefore, canopy Fs has important impacts on ecosystem NEE for tall vegetation such as forests (Hollinger et al., 1994; Zhang et al., 2010) and cannot be ignored in carbon source-sink assessments.

(2) CO flux and concentration show clear seasonal variation characteristics. The annual mean CO flux was −0.079 mg · m^{2} · s^{1} and the annual mean CO concentration was 664.7 mg · m^{3}. CO concentration in the non-growing season was higher than in the growing season, primarily controlled by seasonal changes in CO source-sink intensity caused by plant phenology, and also influenced by regional CO source emissions in the PRD region.

(3) This study estimated the annual mean NEE of the Dinghu Mountain forest ecosystem in 2012 as −611 gC · m^{2} · a^{1}, which is higher than the 2003 flux

observation results from Dinghu Mountain and subtropical artificial coniferous forests, and significantly higher than northern Chinese and North American forests, following the universal pattern of decreasing NEE with increasing latitude. This indicates that the mixed conifer-broadleaf forest at Dinghu Mountain has been growing rapidly in recent years, enhancing its carbon sink function. This may be related to Dinghu Mountain' s location on the western side of the PRD, where it is significantly influenced by human activities including high population density, rapid urbanization, and rapid economic growth in the PRD region, causing annual increases in regional CO concentration since 2003. Satellite remote sensing data show that the annual growth rates of tropospheric CO column concentration in western Guangdong and the PRD region from 2003 to 2009 were 1.82×10 /a and 1.65×10 /a, respectively, both higher than the global average during the same period (Mai et al., 2014). Additionally, Dinghu Mountain has abundant light, temperature, and water resources that facilitate rapid growth of forest vegetation toward zonal communities, promoting CO absorption and strengthening its carbon sink function.

(4) CO flux, NEE, and CO concentration are significantly negatively correlated with air temperature and vapor pressure deficit (VPD), and significantly positively correlated with relative humidity and horizontal wind speed. Air temperature and VPD are the key meteorological factors affecting CO concentration and flux.

Furthermore, forest ecosystem carbon budgets are also related to photosynthesis and respiration of understory vegetation and soil respiration. Previous studies have shown that understory respiration and soil respiration play important roles in the carbon source-sink function of mixed forest ecosystems, with intensities accounting for 30%-80% of total ecosystem respiration (Davidson et al., 2006; Zheng et al., 2009). Due to the lack of radiation and soil temperature observations in this study, ecosystem total respiration (Reco) could not be calculated, potentially leading to larger errors in NEE estimation.

References

ANTHONI PM, LAW BE, UNSWORTH MH, 1999. Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem[J]. Agr Forest Meteorol, 95(3):151-168.

AUBINET M, CHERMANNE B, VANDENHAUTE M, et al, 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes[J]. Agr Forest Meteorol, 108(4):293-315.

AUBINET M, GRELLE A, IBROM A, et al, 1999. Estimates of the Annual Net Carbon and Water Exchange of Forests: The EUROFLUX Methodology[J]. Advan Ecol Res, 30(1):113-175.

BALDOCCHI DD, HICKS BB, MEYERS TP, 1988. Measuring biosphere atmosphere exchanges of biologically related gases with micro-meteorological methods. Ecology, 69:1331-1340.

BALDOCCHI DD, VOGEL CA, 1996. Energy and CO2 flux densities above and below a temperate broad-leaved forest and a boreal pine forest. Tree Physiol, 16:5-16.

BLACK TA, DENHARTOG G, NEUMANN HH, et al, 1996. Annual cycles of water vapor and carbon dioxide fluxes in and above a boreal aspen forest[J]. Global Change Boil, 102:219-229.

BU R, LEI LP, GUO LJ, et al, 2015. Analysis of temporal and spatial potential applications of satellite remote sensing of atmospheric CO2 concentration monitoring. J Remote Sens, 19(1):34-45.

CHEN XF, JIANG H, SUN WW, et al, 2016. Spatiotemporal characteristics of CO2 concentration in *Phyllostachys edulis* forest in Anji during growing season[J]. Chin J Ecol, 35(5):1162-1169.

DAVIDSON EA, RICHARDSON AD, SAVAGE KE, et al, 2006. A distinct seasonal pattern of the ratio of soil respiration to total ecosystem respiration in a spruce-dominated forest[J]. Global Change Boil, 12(2):230-239.

DENG XJ, BI XY, WU D, et al, 2006. An observational study on land-air interaction over grass in Guangzhou Panyu area[J]. J Appl Meteorol Sci, 17(1):59-66.

DIAO YW, HUANG JP, LIU C, et al, 2015. A Modeling Study of CO2 Flux and Concentrations over the Yangtze River Delta Using the WRF-GHG Model[J]. Chin J Atmos Sci, 39(5):849-860.

FALGE E, BALDOCCHI DD, OLSON RJ, et al, 2001. Gapfilling strategies for defensible annual sums of net ecosystem exchange[J]. Agr Forest Meteorol, 107:43-69.

GARRATT JR, 1975. Limitations of the Eddy-correlation technique for the determination of turbulent fluxes near the surface[J]. Bound-Lay Meteorol, 8(3-4):255-259.

GRIFFIS TJ, BLACK TA, MORGENSTERN K, et al, 2003. Ecophysiological controls on the carbon balance of three southern boreal forests[J]. Agr Forest Meteorol, 117:53-71.

GUAN DX, WU JB, YU GR, et al, 2004. Influence of meteorological conditions on CO2 flux of broad-leaved Korean pine forest in Changbai Mountain[J]. Sci China Ser D, 34(S2):103-108.

HE QJ, ZHOU GS, ZHOU L, et al, 2006. Model comparisons for estimating water and heat fluxes of reed wetland ecosystem in Panjin[J]. J Meteorol Environ, 22(4):35-41.

HOLLINGER DY, KELLIHER FM, BYERS JN, et al, 1994. Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere[J]. Ecology, 75(1):134-150.

JARVIS PG, 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field[J]. Phil Trans Roy Soc London B, 273:593-610.

JIA QY, ZHOU GS, WANG Y, et al, 2010. Characteristics of CO2 flux before and in the heating period at urban complex underlying surface area[J]. Environ Sci, 31(4):844-849.

JIAO Z, WANG CK, WANG XC, 2011. Spatio-temporal variations of CO2 concentration within the canopy in a temperate deciduous forest, Northeast China[J]. Chin J Plant Ecol, 35(5):512-522.

LAW BE, BALDOCCHI DD, ANTHONI PM, 1999. Below-canopy and soil CO2 fluxes in a ponderosa pine forest[J]. Agr Forest Meteorol, 94(3-4):171-188.

LEE XH, 1998. On micrometeorological observations of surface-air exchange over tall vegetation[J]. Agr Forest Meteorol, 91(1-2):39-49.

LEE XH, JOSE DF, RALF MS, et al, 1999. Long-term observation of the atmosphere exchange of CO2 with a temperate deciduous forest in southern Ontario, Canada[J]. J Geophys Res, 104:15975-15984.

LIU YF, SONG X, SUN XM, et al, 2004. Seasonal changes of CO2 flux and the effects of environmental factors on the artificial coniferous forest of the thousand tobacco[J]. Sci China Ser D, 34(S2):109-117.

MAI BR, AN XQ, DENG XJ, et al, 2014. Simulation analysis and verification of surface CO2 flux over Pearl River Delta, China[J]. China Environ Sci, 34(8):1960-1971.

MAI BR, DENG XJ, AN XQ, et al, 2014. Spatial and temporal distributions of tropospheric CO2 concentrations over Guangdong province based on satellite observations. China Environ Sci, 34(5):1098~1106.

MICHAEL LG, Bruce C D, Fan S M, et al, 1997. Physiological responses of a black spruce forest to weather[J]. J Geophys Res, 102:28987-28996.

MIN JH, ZHOU GY, ZHANG DQ, et al, 2003. Spatial and temporal variations of some hydrological factors in a climax forest ecosystem in the Dinghushan region[J], Acta Ecol Sin, 23(11):2359-2366.

NISBET MC, MYERS T, 2007. The polls-trends: Twenty years of public opinion about global warming[J]. Public Opin Quart, 71:444-470.

PENG FJ, GE JW, LI YY, et al, 2017. Characteristics of CO2 flux and their effect factors in Dajiuhu Peat Wetland of Shennongjia[J]. Ecol Environ Sci, 26(3):453-460.

PRENTICE IC, FARQUHAR GD, FASHAMM JR, et al, 2011. The carbon cycle and atmosphere CO2. The Intergovernmental Panel on Climate Change (IPCC), Third assessment report, Cambridge: Cambridge University Press:112-113.

RICHARD GA, PEREIRA LS, RAES D, et al, 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements[D]. Rome, Italy: FAO Irrigation and Drainage:201-202.

ROGERS DJ, HAY SI, PACKER MJ, 1996. Predicting the distribution of tsetse flies in West Africa using temporal Fourier processed meteorological satellite data[J]. Ann Trop Med Parasitol, 90:225-241.

ROLLINGER JL, STRONG TF, GRIGAL DF, 1998. Forested soil carbon storage in landscapes of the Northern Great Lakes region[J]. Manage Carbon Sequestration Soil, 335-350.

SAEKI T, MAKSYUTOV S, SAITO M, et al, 2013. Inverse modelling of CO2 fluxes using GOSAT data and multi-year observations[J]. Sola, 9(4):45-50.

SCHOTANUS P, NIEUWSTADT FTM, BRUIN HAR, 1983. Temperature measurements with a sonic anemometer and its application to heat and moisture fluxes[J]. Bound-Lay Meteorol, 26(1):81-93.

SUN CJ, WANG CL, SHEN SH, et al, 2012. Seasonal characteristics of CO2 fluxes above urban green space in the Pearl River Delta, China. Acta Ecol Sin, 32(4):1273-1282.

TAN ZH, ZHANG YP, YU GR, et al, 2008. Spatial and temporal dynamics of CO2 concentration and its causes in Xishuangbanna tropical seasonal rain forest, China[J]. Chin J Plant Ecol, 32(3):555-567.

WANG CL, YU GR, ZHOU GY, et al, 2006. Estimation of CO2 flux in evergreen coniferous and broad-leaved mixed forest in Dinghushan[J]. Sci China Ser D, 36(S1):119-129.

WANG CL, ZHOU GY, WANG X, et al, 2007. Energy balance analysis of the coniferous and broad-leaved mixed forest ecosystem in Dinghushan[J]. J Trop Meteorol, 23(6):643-651.

WANG JM, WANG WZ, AO YH, et al, 2007. Turbulence Flux Measurements under Complicated Conditions[J]. Advan Earth Sci, 22(8):791-797.

WEBB EK, PEARMAN GI, LEUNING R, 1980. Correction of flux measurements for density effects due to heat and water vapour transfer[J]. Quart J Roy Meteorol SOC, 106(447):85-100.

WOFSY SC, GOULDEN ML, MUNGER JW, et al, 1993. Net exchange of CO2 in a mid-latitude forest[J]. Science, 260:13154-1317.

WU JB, GUAN DX, ZHAO XS, et al, 2005. CO2 concentration character in broad-leaved Korean pine forest of Changbai Mountains[J]. Chin J Appl Ecol, 16(1):49-53.

XU YF, JI H, HAN JG, et al, 2018. Variation of net ecosystem carbon flux in growing season and its driving factors in a poplar plantation from Hung-tse Lake wetland[J]. Chin J Ecol, 37(2):322-331.

XU ZW, XIAO RB, DENG YR, et al, 2016. Carbon dioxide emission from urban wetland of the Haizhu Lake[J]. Chin J Appl Environ Biol, 22(1):13-19.

ZHANG FW, LI YN, CAO GM, et al, 2012. CO2 fluxes and their driving factors over alpine meadow grassland ecosystems in the northern shore of Qinghai Lake, China[J]. Chin J Plant Ecol, 36(3):187–198.

ZHANG HM, WU BF, MIN NN, 2014. Remote sensing estimates of vapor pressure deficit: An overview[J]. Advan Earth Sci, 29(5):559-568.

ZHANG M, WENG XF, YU GR, et al, 2010. Effects of CO2 storage flux on carbon budget of forest ecosystem[J]. Chin J Appl Ecol, 21(5):1201-1209.

ZHANG QM, HUANG ZL, LIU SZ, et al, 2002. The community structure of *chinensis Schima Pinus massoniana* broadleaf mixed forest in Dinghu mountain[J]. Stud Trop Subtrop For Ecosyst, 9:18-27.

ZHENG ZM, ZHANG M, WENG XF, et al, 2009. Contributions of below-canopy CO2 fluxes to ecosystem carbon budget of a temperate mixed forest in Changbai Mountain[J]. Acta Ecol Sin, 29(1):1-8.

ZHOU CY, ZHOU GY, ZHANG DQ, et al, 2004. Study on CO2 flux and its influencing factors in Dinghu mountain[J]. Advan Earth Sci, 34(S2):175-182.

ZHOU GS, WANG YH, XU ZZ, 2003. Progress of the study on carbon cycle along NECT[J]. Prog Nat Sci, 13(9):917-922.

Note: Figure translations are in progress. See original paper for figures.