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Research paper

Topographic Effects on CO_2 Flux Measurements at the Chi-Lan Mountain Forest Site

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【Summary】

The multiple eddy covariance measurement approach was applied to discern topographic effects on CO_2 flux measurements at the Chi-Lan Mountain (CLM) site, northern Taiwan. The results suggested that fluxes diverged between different heights above the canopy in the morning. Mean morning CO_2 fluxes at 24 m in height on the main tower (T1) and 26 m in height on the second tower (T2L1) were respectively -15.3 and -14.8 μmol m^{-2} s^{-1} in summer of 2007, while the value was -11.9 μmol m^{-2} s^{-1} at 22 m in height on the second tower (T2L2). The measured fluxes of T2L2 were respectively 22 and 20% lower than those of T1 and T2L1. In addition, we propose that complex CO_2 transport regimes evolve beneath the canopy during transitions of foggy/clear, day/night, and valley-wind/mountain-wind regimes. Under foggy conditions in the late afternoon and early evening, intermittent turbulence dominated and sporadically penetrated downward into the forest. Either vertical eddy flux (-1.4 μmol m^{-2} s^{-1}) or storage change (0.4 μmol m^{-2} s^{-1}) significantly contributed to net ecosystem exchange (NEE) of CO_2 (-1.0 μmol m^{-2} s^{-1}). As the fog dissipated and the atmosphere became stable in the evening, significant decreases in eddy flux plus storage change (from 3.5 to 2.3 μmol m^{-2} s^{-1}) reflected that drainage flow was generated below the canopy and carried CO_2 released from the soil and understory vegetation respiration downhill. The drainage effect consequently led to a 34% underestimation of the nighttime NEE. Our results revealed that topographic effects could respectively bias daytime and nighttime NEE estimations by 20~22 and 34%, which were previously reported at 20~80%. The topographic effects led to evident uncertainties in NEE estimates, and further research is urgently needed to develop adequate data-filtering or correction approaches.

Key words: eddy covariance, advection, storage, cloud forest.

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研究報告

地形效應對棲蘭山森林樣站二氧化碳通量量測的影響

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摘要

本研究採用多套渦度相關儀器方法，以檢測地形效應對於棲蘭山森林樣區二氧化碳通量量測的影響。本研究結果顯示通量發散主要發生於早晨時段、冠層上不同高度的通量量測系統之間。此時段二號塔22公尺處(T2L2)的平均二氧化碳通量為-11.9 μmol m^{-2} s^{-1}，二號塔26公尺處(T2L1)與一號塔24公尺處(T1)則分別為-14.8和-15.3 μmol m^{-2} s^{-1}。T2L2所量測的二氧化碳通量分別比T1與T2L1所量測的通量低22與20%。除此之外，透過垂直剖面、通量及氣象參數的量測，本研究發現棲蘭山樣區每日的起霧/晴天、山風/谷風及晝夜變化形塑了各時段不同的二氧化碳傳輸型態。下午至傍晚起霧時段，紊流發展較弱且主要為間歇性的渦流。渦流通量(-1.4 μmol m^{-2} s^{-1})與暫存量(0.4 μmol m^{-2} s^{-1})皆佔淨生態系二氧化碳交換(-1.0 μmol m^{-2} s^{-1})不可忽略的比例。入夜後隨著天氣型態由有霧轉晴，大氣趨於穩定，渦流通量與暫存量總和顯著地下降(3.5下降至2.3 μmol m^{-2} s^{-1})。此短時間內的下降現象反應出冠層下泄流現象的生成，將土壤及地表植被呼吸所釋放的二氧化碳向下坡方向帶離生態系，總計約造成了約34%的淨生態系二氧化碳交換低估。本研究闡述地形效性造成白天與夜晚淨生態系二氧化碳交換20~22與34%的偏差，與近期相關研究相近(20~80%)。此顯著的地形效應需要更多後續研究，以發展合適的通量資料校正或檢核方法。

關鍵詞：渦流相關法、平流效應、暫存效應、雲霧森林。

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INTRODUCTION

The eddy covariance method provides reliable ecosystem-scale CO_2 flux measurements and has been widely applied in recent decades (Dabberdt et al. 1993, Baldocchi 2003, Yi et al. 2010, Tan et al. 2012). This micrometeorological approach has advanced in terms of its area-integrated representation and continuous measuring characteristics, and also can be conducted in situ without disturbing the environment around the plant canopy (Baldocchi et al. 1988).

A simplified widely accepted estimation of net ecosystem exchange (NEE) of CO_2 is given as (e.g., Finnigan 1999, Finnigan et al. 2003, Feigenwinter et al. 2008):

$$\begin{aligned} \mathrm{NEE} &= \int_0^{zr}\frac{\partial\overline{\rho}_c}{\partial t}dz + \int_0^{zr}\overline{w}\frac{\partial\overline{\rho}_c}{\partial z}dz + \\ &\quad \int_0^{zr}\left[\overline{u}\frac{\partial\overline{\rho}_c}{\partial x} + \overline{v}\frac{\partial\overline{\rho}_c}{\partial y}\right]dz + \overline{w'\rho'_c}(zr) \\ &= \mathrm{Sc} + \mathrm{Fadv} + \mathrm{Fadh} + \mathrm{Fc}; \end{aligned}$$

where NEE is the sum of biological sources/sinks of CO_2 fluxes, ρ_c is the CO_2 concentration, t is the time, zr is the height of eddy flux measurement, and u, v, and w are respective wind velocity components in the x, y, and z coordinate axes. Overbars and primes refer to Reynolds averaging operators. The first term on the right-hand side is the storage change in CO_2 (Sc), and indicates the CO_2 accumulated or decreased in the air beneath the flux measurement height. The second and third terms on the right-hand side are vertical (Fadv) and horizontal (Fadh) CO_2 advection fluxes, respectively. Both advection terms refer to nonturbulent CO_2 transport driven by the mean flow. The fourth term on right-hand side is the vertical CO_2 eddy flux (Fc), which is measured by the eddy covariance method on a tower above the canopy. Under ideal meteorological conditions and satisfactory fetch requirements, the advection terms are relatively negligible compared to the other terms, and hence only the vertical eddy flux and storage change need to be measured to obtain NEE at flux sites (Aubinet et al. 2000).

As held by most flux studies (e.g., Hollinger et al. 2004, Feigenwinter et al. 2008), the vertical eddy flux above a homogeneous canopy is widely assumed and accepted to be horizontally and vertically homogeneous, and hence a single-point flux measurement is capable of characterizing the overall response of the ecosystem. However, increasing numbers of studies have indicated that this assumption does not always hold true when flux measurements are influenced by topographic effects (e.g., advection in Feigenwinter et al. (2008) or flux divergence in Lee (1998) and Wang et al. (2005)). An approach of comparing multiple eddy covariance systems was developed to test the flux homogeneity above the canopy and discern topographic effects (e.g., Yi et al. 2000, Lee and Hu 2002, Kominami et al. 2003, Hollinger and Richardson 2005, Wang et al. 2005). Those recent reports documented that topographic effects could respectively result in 20~36% and 27~80% divergences in horizontal and vertical flux.

In addition, drainage flow generated by gravity and cold stratification beneath the canopy was also found to bias flux measurements in some studies (e.g., Froelich et al. 2005, Marcolla et al. 2005, Froelich and Schmid 2006). This drainage flow can pose uncertainties especially with nighttime flux measurements because turbulence is usually less developed at night. CO_2 transport regimes beneath the canopy could become decoupled from those above canopy, and the CO_2 released by soil respiration might not be detected by sensors above the canopy (Froelich and Schmid 2006). Consequently, drainage effects biased NEE estimations and led to 21~39% underestimations of the nighttime NEE, as reported by Staebler and Fitzjarrald (2004) and Marcolla et al. (2005).

In this study, we examined the topographic effects on flux measurements at a mountain forest site in Taiwan. The objectives of the study were (1) to test the flux homogeneity above the forest canopy; and (2) to explore whether drainage flow is generated below the canopy in this sloping forest site.

MATERIALS AND METHODS

Site description

The Chi-Lan Mountain (CLM) site in northeastern Taiwan (24°35’N, 121°25’E, 1650 m in elevation) is a subtropical montane cloud forest characterized by frequent fog throughout the year. The climate is generally warm with a mean air temperature of 13.9℃ and annual rainfall of 4270 mm yr^{-1} (2003~2007). The site is located on a relatively homogeneous southeastern-facing slope and extends 2 km with an average slope of 14% (Fig. 1). Yellow cypress (*Chamaecyparis obtusa* var. *formosana*) which regenerated naturally since the 1960s is the dominant tree species and accounts for 82% of the total basal area of the stand, whereas 32 other broad leaf tree species share the remaining 18% of the basal area (Chang et al. 2006). The canopy is closed and uniform, with tree heights ranging 11~13 m. A tower (23.4 m high) for

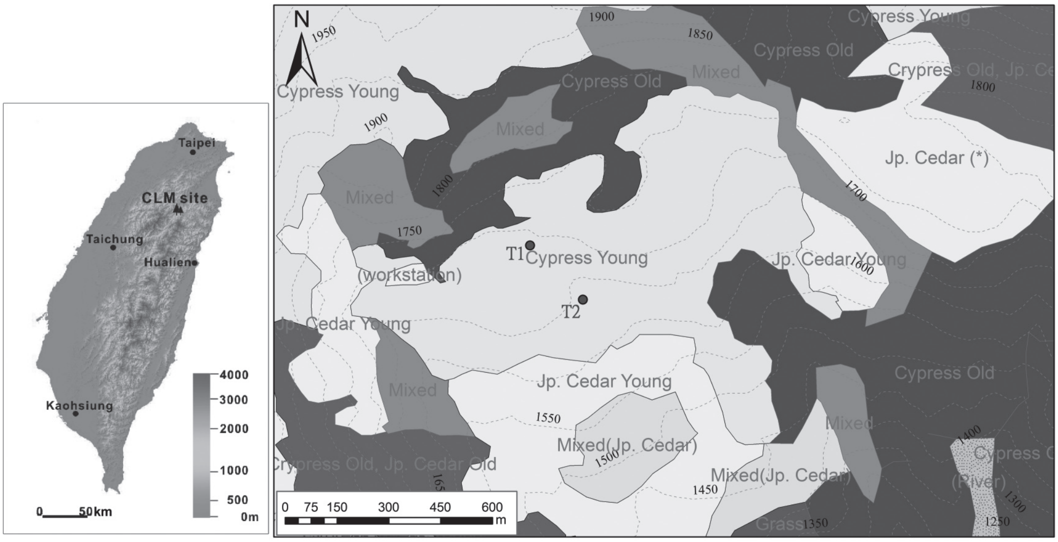

Fig. 1. Vegetation map of the Chi-Lan Mt. (CLM) site. The main (T1) and second (T2) towers are labeled. Dashed lines represent the contours. Cypress, *Chamaecyparis obtusa* var. *formosana*; Jp. Cedar, *Cryptomeria japonica*, Mixed, mixture of young and old trees.

routine meteorological measurements was built within the yellow cypress stand in July 2002. Meteorological parameters have been measured and recorded at this main tower since July 2002 (Chang et al. 2006). A second tower (26 m high) located 200 m to the southeast, downslope from the main tower was constructed in May 2006. The second tower mainly serves as an additional eddy flux measurement location, and its elevation is 40 m lower than the main tower.

The wind and fog regimes, especially during the summer (July-September), show a clear diurnal pattern. In the daytime, wind blows from a southeasterly direction (valley wind) and is frequently associated with fog occurrence in the afternoon. The fog typically persists until evening and gradually dissipates before midnight. Thereafter, the wind changes and blows from a northerly direction (mountain wind) which prevails through the subsequent nighttime (Klemm et al. 2006, Beiderwieden et al. 2007).

To the southeast, a relatively homogeneous yellow cypress stand extends up to 350 m from the main tower. The area beyond that distance is mainly occupied by Japanese cedar (*Cryptomeria japonica*) mixed with broad leaf tree species. A mosaic of forest patches of young and 400-yr-old mature yellow cypress extends 1 km up to the crest in the upslope direction north of the main tower. Based on the valley/mountain wind regime, the daytime and nighttime fluxes mainly originate from the downslope and upslope yellow cypress stands (Mildenberger et al. 2009), respectively. Although the site is not located on flat terrain, it is probably one of the few really good available forest sites in terms of eddy flux measurements in mountainous regions of Taiwan (Klemm et al. 2006, Beiderwieden et al. 2007).

Instrumentation and methodology

An open-path eddy covariance system, consisting of a sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA (CSI)) and an infrared gas analyzer (LI7500, LiCor, Lincoln, NE, USA (LICOR)), was installed at 24 m on the main tower (hereafter referred to as T1), and served as a long-term eddy flux measurement system at the CLM site. Two additional open-path eddy covariance systems were mounted at 26 (hereinafter referred to as T2L1) and 22 m (hereinafter referred to as T2L2) on the second tower in summer of 2007 (July 28~September 20). Each of the additional systems consisted of a sonic anemometer (T2L1: R3-50, Gill Instruments, Hampshire, UK; T2L2: 81000, R. M. Young, Traverse, MI, USA (RMY)) and an LI7500 infrared gas analyzer (LICOR). The raw data, including 3-dimensional velocities, temperature, and CO_2 concentrations, were sampled with a 10-Hz frequency and recorded on a CR5000 datalogger (CSI). Differences in eddy fluxes among these 3 systems were used to discern topographic effects. Manual zero and span calibrations of each gas analyzer were conducted in situ before the experiment began in July 2007. Calm tests for the sonic anemometers were conducted in the laboratory before the experiment, and all 3 anemometers showed reasonable zero offsets according to factory specifications.

In summer of 2008 (July 1~ September 28), a multiple-layer CO_2 concentration and air-temperature profile measurement system was added to the main tower to evaluate storage changes and profile dynamics. The sampling heights of CO_2 concentration were 24, 16, 13.2, 8, 4, 2, 1, and 0.5 m above the ground. Air from each intake was continuously drawn through tubes of comparable length with 8 three-way valves controlled by a CR1000 datalogger (CSI), and air flows were sequentially switched into an LI840 infrared gas analyzer (LICOR). The system was designed to minimize the delay time between sampling positions, and also to eliminate any systematic bias caused by using multiple gas analyzers. The sampling frequency of the gas analyzer was set at 1 Hz, and air from each level was measured for 15 s. The last 3 readings were recorded, and the entire 8-level measurement cycle took 2 min. Air temperatures were measured with fine thermocouple sensors (T-type, Omega Engineering, Stamford, CT, USA), mounted with radiation shields at 24, 18, 16, 13.2, 8, 5.2, 3.6, 2, and 0.4 m above the ground. The sampling frequency was also 1 Hz, and 2-min average values were recorded with a CR23X datalogger (CSI).

We acknowledge the disadvantages in conducting multiple eddy covariance and profile measurements at different periods in the 2 yr. As advection or drainage measurements require extremely intensive instrumentation and field infrastructure, only a small portion of flux sites worldwide have attempted to quantify topographic effects. Aubinet (2008) suggested that both the regimes and magnitudes of advection can strongly vary from site to site. In order to understand possible uncertainties induced by topographic effects, a series of site-specific and intensive measurements is required to first identify the advection patterns and hence improve the quality of screening in processing the flux data. In the study, we targeted topographic effects both above and beneath the canopy. The experiment design was constrained by the available instrumentation in each period, and hence the study was conducted in 2 consecutive summers, targeting above- and beneath-canopy advection, respectively. Both summer periods were characterized by similar climate patterns (foggy afternoons/clear nights) and wind regimes (mountain/valley winds), which are thought to be the major driving factors of advection (in addition to topography) (Massman and Lee 2002). The 2 summer experiments should be capable of elucidating general patterns of topographic effects at the CLM site.

Meteorological parameters were measured on the main tower during the experimental period, including net radiation (CNR-1, Kipp and Zonen, Delft, the Netherlands, at 22.5 m), photosynthetically active radiation (PAR) (LI190, LICOR; at 23.6 m), visibility (Mira 3544, Aanderaa Data Instruments, Bergen, Norway; at 22.0 m), air temperature and relative humidity (41382, RMY; with an aspired fan, at 23.6 m), and soil temperature (type T thermocouples; at 0.1 m in depth). Precipitation was measured with a tipping bucket (TIC-1, Takeda Instrument, Tokyo, Japan) in a nearby cleared area. All parameters were sampled every second, and 10-min averages were recorded by the CR5000 datalogger (CSI). In the study, day and night were classified according to measured PAR ($>$ 5 μmol m^{-2} s^{-1} as day), and foggy conditions were defined as visibility of $<$ 1000 m according to the World Meteorological Organization's definition. Valley and mountain winds were defined as wind respectively blowing from 80°~180° and 280°~10°.

Vertical eddy fluxes were calculated using the eddy covariance method, following the ASIAFLUX methodology in Monji et al. (2003). First, the raw data quality was checked according to the statistical characteristics (Vickers and Mahrt 1997). Second, time lags between the measured scalars and vertical velocity were removed (McMillen 1988), and the planar fit method was applied to rotate the 3 velocity components into the mean streamline coordinate system (Paw U et al. 2000, Wilczak et al. 2001). Third, raw sonic temperatures were corrected with fluctuations of water vapor concentrations to obtain true temperatures (Schotanus et al. 1983). Fourth, a 30-min blocking average without detrending was used (Moncrieff et al. 2004), and the Webb-Pearman-Leuning correction was applied to correct fluctuations in air density (Webb et al. 1980). Finally, stationarity and integral turbulence characteristics of each 30 min of data were calculated and qualitatively flagged (Foken and Wichura 1996, Foken et al. 2004). All calculations were processed with the free software EdiRe (Univ. of Edinburgh, v1.4.3.175, 2009). Additional data screening for heavy rainfall periods was also carried out to exclude possible erroneous data. When comparing CO_2 fluxes measured at different locations, all 3 eddy fluxes were checked each 30 min with respect to the above-mentioned quality criteria and the maximal deviation of wind direction between each measurement (within ±22.5°).

Storage change was calculated each 30 min following the methodology suggested by Mammarella et al. (2007). The stability (z/L) and friction velocity (u^*) were calculated as shown in Kaimal and Finnigan (1994). Finally, the vertical velocity was estimated every 30 min as the residual vertical velocity after the planar fit method (Paw U et al. 2000, Wilczak et al. 2001). In the study, positive signs of eddy fluxes and storage changes respectively indicated net fluxes outward from and net accumulation within the ecosystem.

Statistical analysis

In comparing fluxes measured among T1, T2L1, and T2L2, data were first grouped into morning (06:00~12:00), afternoon (12:00~18:00), and nighttime periods (18:00~06:00). To compare fluxes and meteorological variables among different weather conditions, data were first grouped into foggy afternoons, and foggy and non-foggy nights. The normality and homoscedasticity of each group were then examined. All data used in the study passed normality tests, and hence no transformation or alternative non-parametric analyses were needed. An analysis of variance (ANOVA) test was applied to test differences among locations and weather conditions. Tukey's post-hoc test was adopted to test differences between groups if necessary. All statistical tests were carried out with STATISTICA 7.0 software (StatSoft, Tulsa, OK, USA), and the significance level was set to 0.05.

RESULTS

The climate was generally warm and moist during the experimental period; however, incident radiation and total precipitation showed inter-summer variations (Table 1). PAR was 18% higher in 2007 than in 2008, with respective mean values of 489 and 414 μmol m^{-2} s^{-1}. Associated with less-frequent fog occurrence in the morning, maximal values of diurnal PAR occurred around 10:00 in both summers (Fig. 2a). In total, fog respectively accounted for 20.7 and 17.7% of the time in the summers of 2007 and 2008. The cumulative precipitation reached 2718.5 mm in summer of 2008 but was only 1517.5 mm in summer of 2007. The large inter-summer rainfall difference was mainly contributed by typhoon rainfall (Table 1).

Diurnal courses of CO_2 fluxes showed similar patterns in the 2 summers, rising quickly after dawn and reaching a peak at around 10:00 in the morning (Fig. 2b). This daytime CO_2 flux pattern generally followed the pattern of PAR (Fig. 2a). There were differences in magnitude in daytime fluxes between the 2 summers, mainly reflecting the inter-summer variation in PAR (Fig. 2a). After sunset, CO_2 fluxes turned positive and remained at ~2 μmol m^{-2} s^{-1} throughout the night. Mean daytime CO_2 eddy fluxes at T1 in 2007 and 2008 were -10.0 and -6.4 μmol m^{-2} s^{-1}, while nighttime fluxes were 2.6 and 2.2 μmol m^{-2} s^{-1}, respectively. Negative values indicated that the forest acted as a net CO_2 sink during the daytime, while positive values indicated a net CO_2 source during the night.

CO_2 storage changes were relatively negligible in magnitude with respect to eddy fluxes (Fig. 2b). The daytime and nighttime storage changes averaged -0.1 and 0.1 μmol m^{-2} s^{-1} throughout the summer of 2008, accounting for only 2 and 5% of the eddy fluxes, respectively (Fig. 2b). There were marginal increases in daytime and nighttime storage changes immediately after sunrise and sunset, reaching around -1.9 and 1.1 μmol m^{-2} s^{-1}, respectively. The orders of magnitude of the eddy fluxes were generally low during the sunrise and sunset periods, and consequently, storage changes became significant in NEE estimates during these periods.

CO_2 eddy fluxes at the 3 locations showed consistent diurnal patterns (Fig. 3), but the magnitude at T2L2 was significantly lower than those of T1 and T2L1 during the morning period (ANOVA with Tukey's post hoc test at $p < 0.05$, Table 2). Mean morning CO_2 fluxes of T1 and T2L1 were respectively -15.3 and -14.8 μmol m^{-2} s^{-1}, while the flux

Table 1. Mean daytime photosynthetically active radiation (PAR), mean air temperature (Ta), mean soil temperature (Tg), accumulated rainfall (Rain), and foggy time percentage (Fog) in summers of 2007 and 2008. Precipitation within the brackets [] indicates rainfall during typhoon event

Period	PAR (μmol m^{-2} s^{-1})	Ta (℃)	Tg (℃)	Rain (mm)	Fog (%)
2007	489	19.1	14.9	1517.5 [1106.5]	20.7
2008	414	19.7	12.6	2718.5 [1880]	17.7

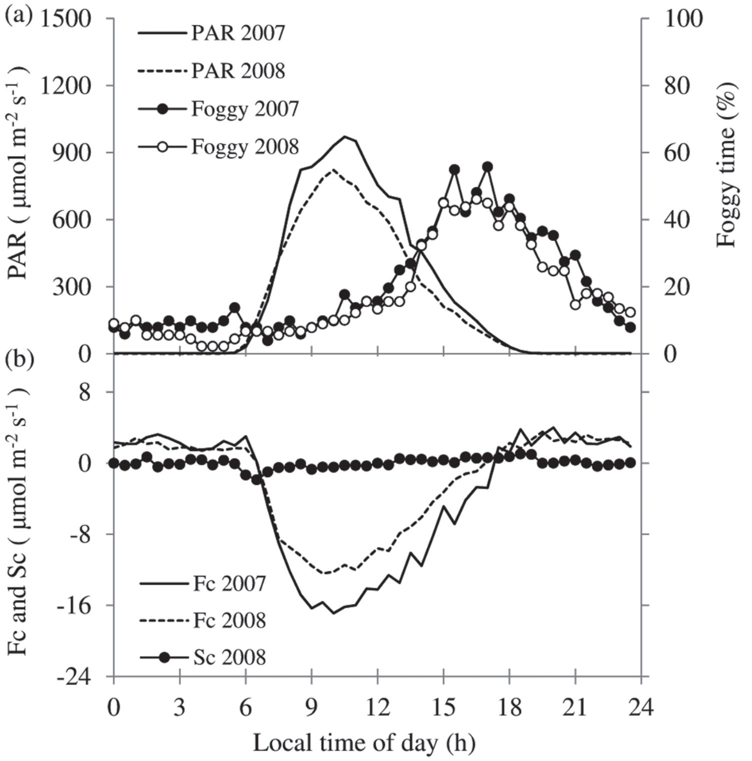

Fig. 2. (a) Mean diurnal photosynthetically active radiation (PAR) and foggy time percentage (Foggy) in summer of 2007 (PAR 2007, foggy 2007) and summer of 2008 (PAR 2008, Foggy 2008). (b) Mean diurnal CO_2 fluxes and storage changes in summer of 2007 (Fc 2007) and summer of 2008 (Fc 2008, Sc 2008). Both eddy fluxes and storage changes were measured at the main tower.

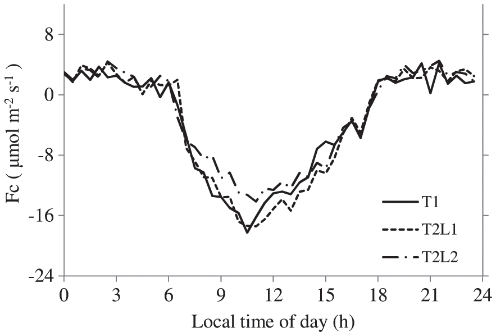

Fig. 3. Comparison of mean diurnal CO_2 eddy flux courses in summer of 2007. Measurements were conducted at 24 m in height of the main tower (T1), and at 26 (T2L1) and 22 m (T2L2) in height of the second tower.

of T2L2 was only -11.9 µmol m^{-2} s^{-1} (22 and 20% lower than those of T1 and T2L1). The significant difference revealed that there was divergence in the measured eddy fluxes between T2L2 and T2L1/T1 (Table 2). In the afternoon and nighttime periods, CO_2 fluxes did not show significant differences among the 3 locations (ANOVA test, $p > 0.05$, Table 2).

The CO_2 concentration profile measured in summer of 2008 showed a clear diurnal course and was associated with the dynamics and distribution of CO_2 sources/sinks of the forest (Fig. 4). CO_2 concentrations respectively averaged 370 and 383 ppm above and beneath the canopy at 05:00 in the morning.

Table 2. Comparison of CO_2 fluxes among 3 locations in summer of 2007. Fluxes were measured at 24 m in height of the main tower (T1), and 26 (T2L1) and 22 m (T2L2) in height of the second tower, respectively. Standard deviations are presented within parentheses (). Different letters (a-b) indicate a statistically significant difference among locations (T1/T2L1/T2L2) at $p < 0.05$ (ANOVA with Tukey's post hoc test)

Location	Fc (μmol m^{-2} s^{-1})		
	Valley wind		Mountain wind
	Morning	Afternoon	Nighttime
T1	-15.3 (5.4) a	-9.1 (5.9) a	2.1 (2.6) a
T2L1	-14.8 (5.3) a	-10.5 (6.8) a	2.8 (2.3) a
T2L2	-11.9 (4.3) b	-9.6 (5.6) a	2.7 (2.0) a

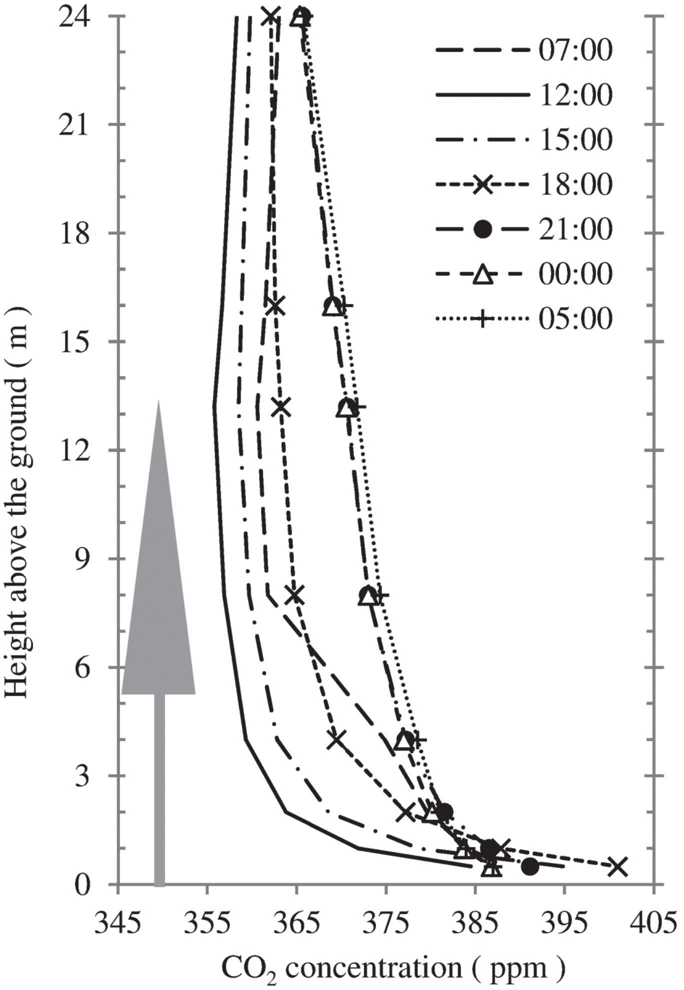

Fig. 4. Mean CO_2 concentration profiles in summer of 2008 on the main tower. Data at local times of 00:00, 05:00, 07:00, 12:00, 15:00, 18:00, and 21:00 are presented. The gray tree indicates average heights of the canopy top and bottom.

From 05:00 to 12:00, CO_2 concentrations showed a general decrease of 2~20 ppm in the profile. The decreasing CO_2 concentration reflected the triggering of photosynthesis and strong uptake of CO_2 by the forest canopy. The CO_2 concentration was consistently higher near the ground (385~404 ppm), revealing a strong CO_2 source of soil respiration. The canopy-sink and soil-source distribution consequently led to a vertical CO_2 gradient of 13~40 ppm between the ground and canopy height through the daytime. After sunset, the forest canopy turned into a CO_2 source via respiration, and CO_2 concentrations gradually increased at all levels. CO_2 concentrations within and above the canopy reached their respective maxima of 373 and 371 ppm at 21:00, and remained steady thereafter throughout the nighttime. Surprisingly, the CO_2 concentration near the ground reached its maximum of 404 ppm around 18:00 and decreased thereafter, regardless of increases in the upper levels.

To further illustrate the complex profile dynamics associated with the transition of day/night, foggy/not-foggy, and valley/mountain wind regimes, a typical summer daily course of August 26~27, 2008 is presented (Fig. 5). In the morning of August 26, evolution of CO_2 concentration profiles was similar to that described above (Figs. 4, 5e). When the weather became foggy around 15:00 in the afternoon (Fig. 5c), both wind speed and net radiation flux decreased during the foggy period (Fig. 5a, c). As friction velocity decreased and stability changed from unstable to near neutral after 15:00 (Fig. 5b), the CO_2 concentration began to increase below the canopy (~430 ppm at 0.5 m high, Fig. 5e). The wind speed and friction velocity rose sporadically in the foggy period (e.g., 16:00~16:30), revealing that turbulence was intermittent and not well developed all the time. Consequently, the CO_2 concentration showed a sudden drop at 16:00~16:30 and a stepwise increasing trend from 16:30 to 19:30. The CO_2 concentration reached 460 ppm near the ground at 19:00~20:00. As the wind direction changed from an upslope to a downslope mountain wind at around 21:00 (Fig. 5a), the fog rapidly dissipated followed by strong radiation cooling (with a net radiation flux of -100 W m^{-2}) and gradually decreasing air temperature below the canopy (up to 2.5℃ lower than above the canopy) (Fig. 5c, f). During this fog and wind regime transition period, CO_2 concentrations below the canopy dramatically decreased within ~2 h (~65 ppm near the ground) and remained steady for the rest of the night (Fig. 5e).

Grouping the 3-mo data by day/night, foggy/non-foggy, and valley/mountain wind direction conditions, the difference in the sum of the CO_2 eddy flux and storage change further indicated that different transport regimes prevailed in different periods. In the afternoon of foggy days, the CO_2 storage change (0.4 μmol m^{-2} s^{-1}) was of a comparable order of magnitude to the CO_2 eddy flux (-1.4 μmol m^{-2} s^{-1}) but had an opposite transport direction (Table 3). After sunset, the sum of the CO_2 eddy flux and storage change was significantly higher when it was foggy along with a valley wind regime (ANOVA with Tukey's post-hoc test, $p < 0.05$, Table 3). The sum of the eddy flux and storage change averaged 2.3 μmol m^{-2} s^{-1} during non-foggy nights, and was 34% lower than foggy nights (3.5 μmol m^{-2} s^{-1}). The major difference occurred in eddy fluxes (ANOVA with Tukey's post hoc-test, $p < 0.05$, Table 3), whereas storage changes showed no significant difference (ANOVA test, $p > 0.05$, Table 3). In the meantime, soil temperatures among these periods did not show significant differences (ANOVA test, $p > 0.05$, Table 3).

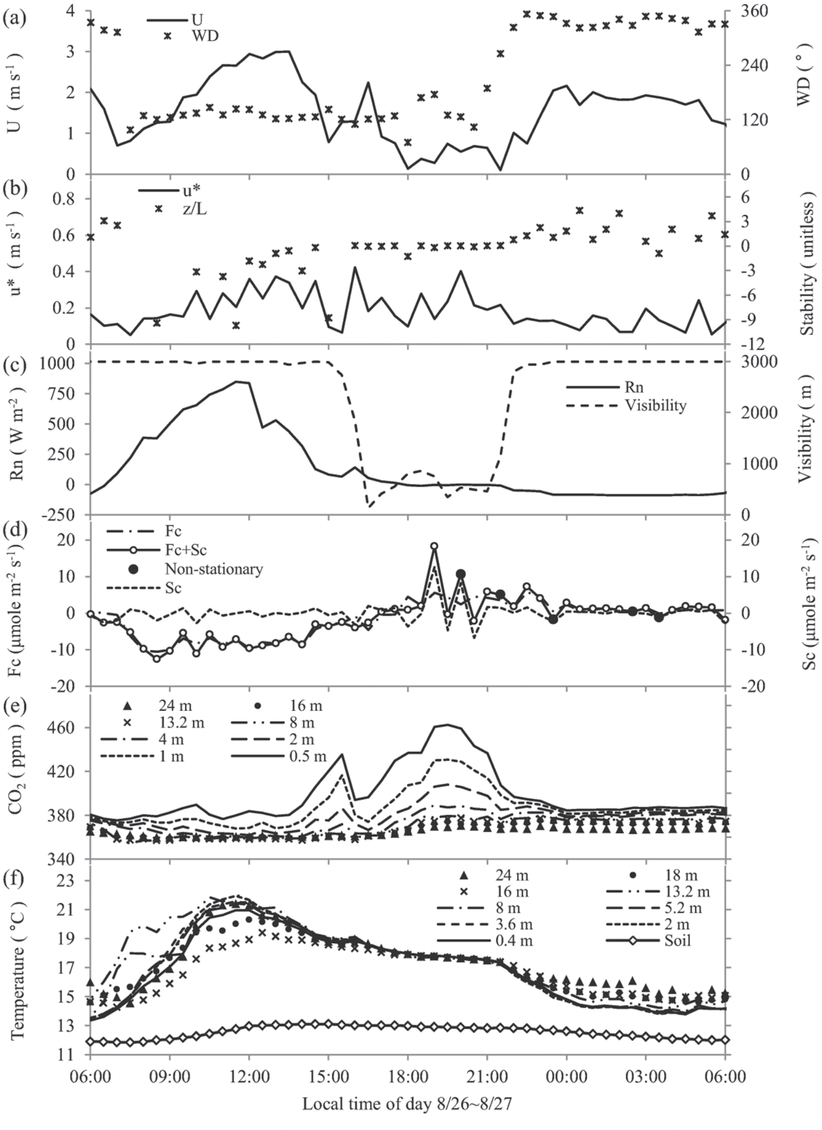

Fig. 5. A representative summer daily course on August 26~27, 2008, including wind speed (U) and wind direction (WD) (a), friction velocity (u^*) and atmospheric stability (z/L) (b), net radiation (Rn) and visibility (c), CO_2 eddy flux (Fc), storage change (Sc), and CO_2 eddy flux plus storage change (Fc + Sc) (non-stationary periods are labeled with closed circles) (d), CO_2 concentration profile (e), and air and soil temperature profiles (f).

DISCUSSION

CO_2 flux homogeneity above the canopy

We propose that the divergence between the 2 heights on the second tower was mainly induced by vertical advection flux. Vertical advection can be attributed to the vertical velocity modulated by the sloping terrain accompanied by a CO_2 concentration gradient. Although we did not directly measure the advection flux in our study, we estimated its possible order of magnitude following Lee

Table 3. Comparison of mean CO_2 eddy flux (Fc), CO_2 storage change (Sc), and soil temperature (Tg) among foggy afternoons, foggy evenings, and non-foggy nights in summer of 2008. Standard deviations are presented within parentheses (). Different letters (a-c) indicates a statistically significant difference among time intervals (foggy afternoons/foggy nights/non-foggy nights) at $p < 0.05$ (ANOVA with Tukey's post hoc test)

Time interval	Wind direction/Weather	Fc + Sc	Fc	Sc	Tg
		(μmol m^{-2} s^{-1})			(℃)
Afternoon	Valley wind/Foggy	-1.0 (0.3)a	-1.4 (0.2)a	0.4 (0.1)a	12.7 (0.1)a
Nighttime	Valley wind/Foggy	3.5 (0.3)b	3.3 (0.2)b	0.2 (0.2)a	12.7 (0.1)a
Nighttime	Mountain wind/Non-foggy	2.3 (0.2)c	2.2 (0.1)c	0.1 (0.2)a	12.7 (0.1)a

(1998). The vertical advection flux can be estimated based on the assumption of a continuity approximation and flux divergence balance. Analogous to Lee's approach, the CO_2 flux difference between T2L1 and T2L2 can be calculated as

$$\Delta Fc = (\bar{\rho}_{c\_T2L1} - \bar{\rho}_{c\_T2L2}) \times (\bar{w}_{T2L1} + \bar{w}_{T2L2})/2;$$

where ΔFc is the CO_2 flux difference between T2L1 and T2L2, and $\bar{\rho}_c$ and $\bar{w}$ are the mean CO_2 concentration and estimated vertical velocity, respectively. The vertical velocity was estimated every 30 min by the planar fit method (Lee 1998), and respectively averaged out to 0.13 and 0.08 m s^{-1} for T2L1 and T2L2 throughout morning times in summer of 2007. Since no profile measurement was available in 2007, the mean CO_2 concentration gradient was approximated as 24 μmol m^{-3} m^{-1} for the 4-m difference in height based on profile measurements at the main tower in 2008. The mean vertical advection flux was then estimated to be 2.6 μmol m^{-2} s^{-1}, with the same order of magnitude as the average flux difference between T2L1 and T2L2 (2.9 μmol m^{-2} s^{-1}). While uncertainties still exist in the estimation of the mean vertical velocity and CO_2 concentration gradient (addressed in Aubinet et al. 2005, Froelich et al. 2005, Marcolla et al. 2005), the compatible order between the estimation and measurement might not directly prove the occurrence of vertical advection under the current experiment design. However, it did provide on insight that the order of magnitude of the advection flux could possibly bias the flux measurement in the sloping terrain.

Complex CO_2 transport regimes evolved beneath the canopy

We propose that intermittent turbulence dominates the CO_2 transport regime under foggy conditions in the late afternoon and evening at the CLM site, and both vertical eddy flux and storage change significantly contribute to NEE. As shown in our results, fog occurrence in the late afternoon was accompanied by lower incident radiation, near neutral stability, non-stationarity, and intermediate winds (Fig. 5). Weak turbulence developed, and intermittent turbulence dominated the transport processes under such conditions (Mahrt 1999, Aubinet 2008). This intermittent turbulence was supported by our observed fluctuations and non-stationarity of CO_2 eddy fluxes (Fig. 5d), as well as by the stepwise (rather than continuous) increasing CO_2 concentration below the canopy (Fig. 5e). During these periods, CO_2 released from the soil and understory vegetation was either transported upward by intermittent turbulence (as the eddy flux term) or accumulated in the air beneath the canopy (as the storage change term). Neglecting either of them would lead to misinterpretation of ecosystem carbon sequestration processes.

We proposed that drainage flow began to be generated beneath the canopy as the wind direction reversed in the late evening and prevailed through the following nighttime. CO_2 released through soil respiration and understory vegetation respiration might not accumulate in the air or be transported upward by turbulence, but brought downhill instead. Our results showed strong radiation cooling and air stratification beneath the canopy during the nighttime (Fig. 5), which were thought to be prerequisites for generating drainage flow in a sloping terrain (e.g., Staebler and Fitzjarrald 2004, Froelich et al. 2005, Froelich and Schmid 2006, Goulden et al. 2006). When the fog dissipated and the weather turned clear in the first half of the night, soil temperatures did not drastically drop (Fig. 5f). The CO_2 released by the soil and understory vegetation respiration was hence expected to remain steady. The drastic decrease in the sum of the vertical eddy flux and storage change (34%) was thus believed to mainly be attributed to a shift in the CO_2 transport regime rather than the CO_2 source strength. The missing CO_2 was carried downhill by drainage flow and was not counted as either eddy flux or storage change.

The shift in nighttime CO_2 transport regimes revealed that the u^* threshold filtering, a widely-adopted approach for nighttime data quality checks (e.g., Goulden et al. 1996, Aubinet et al. 2000, Gu et al. 2005), might be unsuitable in our case. As drainage flow prevailed through the nighttime below the canopy, the u^* value obtained at the top of the tower might not be a suitable indicator for turbulence development within and under the canopy. A new strategy using the maximal sum of the eddy flux and storage change shortly after sunset as the representative nighttime NEE was proposed by van Gorsel et al. (2007, 2008). This strategy might be an alternative data-filtering approach at the CLM site, and additional research such as quantifying the biological CO_2 source/sink strength via plant physiological methods or quantifying drainage flow via meteorological methods is needed.

CONCLUSIONS

Our study clearly showed the topographic effects did create uncertainties in CO_2 flux measurements at the CLM site. First, flux divergence was generated above the canopy during the morning time, and it could reach up to 20~22% of the flux over 2 mo. Second, intermittent turbulence dominated during foggy afternoons and evenings, and either the eddy flux or storage change accounted for significant portions of NEE. Third, drainage flow generated beneath the canopy during clear nights carried CO_2 released by the soil and understory vegetation respiration downhill. Drainage flow could reduce the sum of the eddy flux and storage change by up to 34% during the nighttime.

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