Abstract

This paper reports on the results of a short-term observation of CO₂ flux above a tropical forest at Pasoh in Peninsular Malaysia, using the eddy covariance method with a closed-path CO₂ analyzer, in March 1998. CO₂ concentration profiles above and in a canopy were also measured. In the daytime, the time series of fluctuations in CO₂ concentration above the forest drew the ramp pattern with a period of 2 min. This suggests that large-scale turbulent motions contribute to CO₂ flux in the daytime. We obtained data on the CO₂ flux for 6 days and CO₂ storage flux under the flux measurement level for 3 days in this observation. The values of the CO₂ flux fell within \(-1.0\) to \(0.5\) mg CO₂ m\(^{-2}\) s\(^{-1}\). Net ecosystem CO₂ exchange (NEE) was estimated as the sum of the CO₂ flux and the CO₂ storage flux. Compared with the CO₂ flux, the CO₂ storage flux was relatively large in the early morning and the nighttime; therefore, the storage flux became important to estimate the NEE in those periods. The daily values of the NEE ranged from \(-2.08\) to \(-2.74\) g C m\(^{-2}\) per day. The results suggest that this tropical forest was a CO₂ sink during the period.

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Keywords: CO₂ flux; Eddy-covariance; Net ecosystem CO₂ exchange; Tropical rain forest; Southeast Asia

1. Introduction

Eddy covariance measurements of carbon dioxide (CO₂) flux between a forest ecosystem and the atmosphere is a sound way to evaluate CO₂ uptake by the forest. Continuous observations of CO₂ flux have been conducted for various types of forests, but the vast majority of these sites have been in boreal and temperate forests in Europe and North America. Observation sites in tropical rain forests conducting routine CO₂ flux measurements are probably only in Central and South America.
Direct measurements of CO₂ flux over Amazonian tropical rain forests clearly documented that these forests were a sink of CO₂ at least for a short term period (Fan et al., 1990), and possibly even for a whole year (Grace et al., 1995; Malhi et al., 1998). Tropical rain forests cover 12% of the vegetated surface of the earth (Whittaker and Likens, 1975; Malhi et al., 1998). They play a major role in the global uptake of CO₂ by the biosphere. To investigate this, many more measurements are required for tropical rain forests in different areas.

Aoki et al. (1975) took intermittent measurements of CO₂ flux above a tropical rain forest in Southeast Asia. This experiment was carried out at Pasoh in Peninsular Malaysia (Pasoh forest). Pasoh forest was a study area of the International Biological Program (IBP) in the 1970s. Aoki et al. (1975) estimated the CO₂ flux from vertical CO₂ profiles above the forest in November 1973, and they calculated that the net CO₂ uptake rate by the forest was 1.2 mg CO₂ m⁻² s⁻¹ when the incoming solar radiation was 907 W m⁻².

In the present study, we conducted a short-term measurement of CO₂ flux above the Pasoh forest, adopting the eddy covariance method. Then net ecosystem CO₂ exchange (NEE) of the forest was estimated as the sum of CO₂ flux and the change rate of CO₂ concentration in the air layer below the flux measuring height (Wofsy et al., 1993; Greco and Baldocchi, 1996; Baldocchi et al., 1997). We collected the available data of CO₂ flux for 6 days and CO₂ storage for 3 days during the observation. This experiment was the first attempt to take direct measurements of CO₂ flux above the Pasoh forest, and was carried out to obtain basic knowledge on characteristics of CO₂ flux above a tropical forest in Southeast Asia.

2. Experiment

2.1. Site description

The observation was conducted in Pasoh Forest Reserve of Forest Research Institute Malaysia (FRIM) from 5 to 15 March in 1998. This forest reserve is located about 140 km southeast of Kuala Lumpur in Peninsular Malaysia, and is 2450 ha in area (see Fig. 1). The reserve is mostly covered with lowland mixed dipterocarp forest. The forest contains primary
and secondary forests (about 1650 and 650 ha, respectively), consisting of various species of Shorea and Dipterocarpus (Soepadmo, 1978). The regenerating area was selectively logged between 1955 and 1960 (Manokaran and Kochummen, 1994). Although the continuous canopy height is about 35 m, there are some emergent trees that exceed 45 m. The dry biomass above the ground and the leaf area index (LAI) were estimated as 463.6 t ha$^{-1}$ and 6.25 by tree diameter observation (Niiyama, unpublished), with empirical equations made for this forest (Kato et al., 1978). The topography in the forest is gently undulating. The soils are characterized by the presence of a band of laterite and a compact structure derived from shales within the area of Durian Series, are poor in cations (except for aluminum) and available phosphorus, and have a low pH of pH 3.5–4.8 (Soepadmo, 1978).

The climate of the forest is summarized by Soepadmo (1978). There is little seasonal variation in air temperature. The mean air temperature is 24.8 °C at 3 m above the ground at an open space in the forest. There are two rainy and dry seasons in this region. The rainy seasons are during April–May and October–November, responding the southwest and northeast monsoons, respectively. The mean annual rainfall is about 2050 mm.

The maximum fetch of the forest is about 3500 m to the north and the minimum one is about 800 m to the southeast, so that the ratios of the fetch to the height of the flux-measurement point (52 m) from the continuous canopy height are 206 and 47, respectively. Northerly winds dominated during the observation.

2.2. Measurements

$CO_2$ flux was measured at the top of a 52 m-tall scaffold tower. The closed-path technique was applied to the eddy covariance measurement. Wind speed and temperature were measured with a three-axis sonic anemometer (DA-600, Kaijo), and $CO_2$ concentration was monitored with a closed-path $CO_2/H_2O$ analyzer (LI-6262, LICOR). The sonic anemometer and the inlet of a sampling tube were installed at 52 m. Sample air was drawn through a polyethylene tube (16 m long, 6 mm in diameter) with a diaphragm pump and was pushed by the pump to the $CO_2$ analyzer through a Teflon tube (3 m long, 4 mm in diameter). The flow rates before and after the pump were about 8.5 l min$^{-1}$ and 2.0 l min$^{-1}$. Residual air was exhausted from a vent. The signals from the eddy covariance sensors were sampled at 5 Hz, and directly recorded with a digital data recorder (DRM2a, TEAC).

Two $CO_2$ analyzers were used to measure the vertical profile of $CO_2$ concentrations at six levels above and within the canopy. One analyzer (LI-6252) measured $CO_2$ profile above the canopy (52, 48 and 40 m) at the flow rate of 2.0 l min$^{-1}$ and another one (LI-6251) measured it within the canopy (30, 21 and 11 m) at the flow rate of 0.5 l min$^{-1}$. Sampling heights were changed at 5 min intervals above the canopy and 10 min intervals within the canopy, allowing enough time to flush tubes containing residual air of last sampling.

Meteorological data were also collected at the top of the tower (solar radiation, temperature, humidity, wind velocity, rainfall, etc.). All instruments were powered using a generator put at the base of the tower. The $CO_2$ analyzers were calibrated once or twice a day using $N_2$ and $CO_2$ standard gases. For $H_2O$ output, the LI-6262 was also calibrated using a dew point generator (LI-610, LICOR) as many as $CO_2$ calibrations. $CO_2$ fluxes were calculated using the covariance of vertical wind velocity and the mixing ratio of $CO_2$ (Grelle and Lindroth, 1996) for every 30 min. The three-dimensional coordinate rotation of wind velocity components (McMillen, 1988) was applied to set mean vertical wind velocity on zero ($\bar{w} = 0$). The data of fluctuations in $CO_2$ concentration were detrended by linear least squares fittings to remove diurnal variation. The lag time caused by the air sampling through tubes was 4.8 s determined by the maximum correlation between fluctuations in temperature and those in $CO_2$ concentration.

Frequency correction for the damping of fluctuation at high frequencies was applied to flux calculations. Here, we used the procedure based on the spectral similarity of scalar fluxes (Aubinet et al., 2001). Although the frequency correction increased absolute values of $CO_2$ flux during the day and night, the typical increasing rates were only 1–2% in the daytime and <10% in the nighttime when the magnitudes of $CO_2$ flux were not extremely small. Malhi et al. (1998) mentioned that the frequency correction for the damping ranged from 10 to 25% in the daytime (mean = 16%) and from 10 to 30% in the nighttime (mean = 11%).
above an Amazonian tropical rain forest. Our correction rates were much smaller than their results.

3. Results and discussion

3.1. Fluctuations in CO₂

Fig. 2 shows typical fluctuations in the mixing ratios of CO₂ and H₂O (measured with LI-6262) and air temperature above the Pasoh forest. The data in the figure were collected under unstable conditions and are illustrated by time traces at intervals of 1 s. The mean wind velocity during the period was 1.9 m s⁻¹, and the Monin–Obkov length was ~16.1 m. The amplitude of dominant fluctuation in CO₂ was about 7 mg·kg⁻¹, and fluctuations with a period of about 2 min are apparent. The variations in CO₂ concentration frequently have gradual decreases followed by rapid increases (so-called the ramp pattern). The ramp patterns are also obvious in the time series of humidity and air temperature, although these ramps are inverted because the vertical gradients of humidity and air temperature are opposite to that of CO₂ concentration. We cannot see small fluctuations in humidity at high frequencies, since the damping of humidity fluctuations due to air sampling through a long tube is more serious than CO₂. The ramp patterns are de-
tected above agricultural fields (short vegetation) and forests (Gao et al., 1989; Paw U et al., 1992), and organized turbulent motions that produce the ramp pattern greatly contribute to scalar fluxes (Gao et al., 1989). The fluctuations with a period of about 2 min would account for a large portion of scalar fluxes during the daytime.

### 3.2. Diurnal variations in CO$_2$ flux and NEE

Fig. 3 shows the diurnal variations in CO$_2$ flux, solar radiation, air temperature, water vapor pressure deficit (VPD) and wind speed measured at the top of the tower (52 m). All data are 30 min mean values. The sign convention of the CO$_2$ flux is that downward flux is negative and upward flux is positive. In the afternoon on 10 March (DOY 68), the CO$_2$ flux data could not be obtained because of instrument trouble. During the observation period, the maximum solar radiation was $1080\ W\ m^{-2}$ and mean air temperature was $26.9^\circ\ C$. The maximum VPD was 30.2 hPa, which is very dry for the region. However, it was very humid from midnight to early morning. We observed mist formation in the early morning of almost all days. Two rain events were observed on the nights of DOY 70 (0.73 mm) and DOY 71 (8.0 mm), and the total amount of rainfall was 8.73 mm. Wind speed was generally low, especially in the morning. The lowest wind speed was 0.2 m s$^{-1}$ measured in the morning of DOY 68, and the mean wind speed throughout the period was 1.6 m s$^{-1}$.

For reference, we also show CO$_2$ flux calculated without linear detrending of CO$_2$ data (block-average removal). The simple-mean removal keeps low-frequency components arising from the diurnal variation, which are not related to eddy fluxes. The diurnal variations in CO$_2$ flux clearly document the activity of the forest ecosystem. The values of the fluxes had a range of $-1.0$ to $0.5\ mg\ CO$_2\ m^{-2}\ s^{-1}$ ($-22.7$ to $11.4\ \mu\mol\ m^{-2}\ s^{-1}$). The peaks of the downward CO$_2$ flux appeared earlier than the peaks of the solar radiation on clear days (DOY 67, 69, 72). In such cases, the magnitude of the CO$_2$ flux increased rapidly in the morning, but decreased gradually in the afternoon. A similar variation in CO$_2$ flux was measured above a Brazilian rain forest (Grace et al., 1996).

We obtained data on stored CO$_2$ in the air layer under the flux-measurement height (CO$_2$ storage flux) for 3 days: 9, 11 and 12 March (DOY 67, 69 and 70, respectively). The units of the CO$_2$ storage flux were the same as those of CO$_2$ flux; positive and negative signs indicate the increase and the decrease of stored CO$_2$ in the air layer. Fig. 4 shows the diurnal variations of the CO$_2$ flux ($F_c$), the CO$_2$ storage flux ($F_{storage}$) on 9, 11 and 12 March. The diurnal variations in the net ecosystem exchange (NEE) evaluated as $F_c + F_{storage}$ are also shown in Fig. 4.

We can see $F_{storage}$ has the same order as $F_c$. In the morning, $F_{storage}$ started to decrease earlier than $F_c$, then reached the negative peak in the early morning and increased before $F_c$ reached its negative maximum. These variations mean that trees first consume CO$_2$ stored in the canopy air layer, and later, as the vertical gradient of CO$_2$ becomes large, CO$_2$ flux tends to be downward. After the canopy air layer is well mixed, the contribution of the storage becomes small, however, the low wind conditions in the morning raise the importance of the CO$_2$ stored in the canopy layer.

The NEE represents the net biotic CO$_2$ flux of the forest. The amount of the NEE was larger than that of the CO$_2$ flux during the low turbulence period from night to morning, especially in the morning when the storage flux dominated $F_c$. However, the NEE and $F_c$ had almost the same values in the afternoon, because the changes of stored CO$_2$ in the underlying layer were small ($F_{storage}$ was small) in that period. We confirm that the measurements of CO$_2$ storage during the night and morning were particularly important, when we consider CO$_2$ uptake by a forest ecosystem.

Fig. 5 presents the response of NEE in the Pasoh forest to solar radiation obtained during the daytime on 9, 11 and 12 March. It is clearly shown that the amount of NEE increases as the incident solar radiation increases. However, when the solar radiation is $>800\ W\ m^{-2}$, the NEE seems to be saturated. All plots are distinguished according to the water vapor pressure deficit: VPD $\leq 16\ h\ Pa$ or VPD $>16\ h\ Pa$. Curves in the figure denote rectangular hyperbolas fitted to the plots. When the VPD was $\leq 16\ h\ Pa$, the magnitude of the NEE sharply increased under low light condition (about $<300\ W\ m^{-2}$) and saturated under high light condition. When the VPD was $>16\ h\ Pa$, the magnitude
Fig. 3. Diurnal variations in CO₂ flux above the Pasoh forest, and half-hourly averaged meteorological data (solar radiation, air temperature, water vapor pressure deficit and wind speed) at 52 m height on 8–15 March (DOY 66–73). The broken line in the top figure indicates CO₂ flux calculated from the block-average removal (without linear detrending).
Fig. 4. Diurnal variations in CO₂ flux, CO₂ storage flux and net ecosystem exchange (NEE) on 9 March (a), 11 March (b), 12 March (c) in 1998.
The mean daily value of NEE was \(-2.44 \text{ g C m}^{-2}\) per day. Fan et al. (1990) and Grace et al. (1996) evaluated the daily values of NEE in Amazonian tropical forests as about \(-0.60 \text{ g C m}^{-2}\) per day \((\sim 0.05 \text{ mol m}^{-2}\) per day) calculated from a short-term measurement and \(-0.54 \text{ g C m}^{-2}\) per day \((\sim 0.045 \text{ mol m}^{-2}\) per day) measured during a 44 day-observation. The daily NEE in the Pasoh forest is 4.1–4.5 times that in the Amazonian forest. Moreover, Grace et al. (1996) obtained daily NEE in the Amazonian forest in the dry season as \(-1.08 \text{ g C m}^{-2}\) per day \((\sim 0.09 \text{ mol m}^{-2}\) per day). Our measurements, which were taken on clear days in the dry season, were 2.3 times larger than the daily NEE in the Amazonian forest in the dry season. The daily NEE in this study were correspond to daily NEE of temperate deciduous forests in autumn (Greco and Baldocchi, 1996; Lee et al., 1999).

#### 3.3. Discussion of the mass flow effect on daily NEE

Lee (1998) showed that NEE should be evaluated as the sum of CO₂ flux, CO₂ storage and vertical mass flow (vertical advective flow) arising from non-zero mean vertical wind velocity. Here, we try to calculate the mass flow component, following the procedure suggested by Lee (1998). In our calculation, the true mean vertical velocities were calculated with linear fitting of vertical wind velocity to horizontal wind velocity for every 1° interval in the wind direction. For the present short-term experiment, we made a linear fitting for each wind direction using the wind data in directions of ±20°, thereby increasing the number of data for each regression always larger than 20.

Table 1 shows daily values of CO₂ flux, CO₂ storage, NEE (flux + storage) and vertical mass flow for 3 days. The daily CO₂ flux values were negative for 3 days, while daily CO₂ storage values were negative for 2 days and slightly positive on 11 March. Therefore, the daily NEE values were negative for all days. The daily values of the mass flow component were positive for 3 days. The absolute values of the mass flow were 2.0–4.6 times larger than those of the NEE. Anthoni et al. (1999) and Baldocchi et al. (2000) showed that the amount of CO₂ released from an ecosystem was increased at night when the mass flow component was taken into account. However, according to their estimates, the daily value of mass flow component did not exceed that of the sum of daily CO₂ flux and daily
Table 1

<table>
<thead>
<tr>
<th>Period</th>
<th>CO₂ flux</th>
<th>CO₂ storage</th>
<th>NEE</th>
<th>Mass flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 March</td>
<td>−2.14 (−0.178)</td>
<td>−0.36 (−0.030)</td>
<td>−2.50 (−0.208)</td>
<td>5.02 (0.418)</td>
</tr>
<tr>
<td>11 March</td>
<td>−2.73 (−0.228)</td>
<td>0.01 (8.5 × 10⁻⁴)</td>
<td>−2.74 (−0.228)</td>
<td>12.55 (1.046)</td>
</tr>
<tr>
<td>12 March</td>
<td>−1.51 (−0.126)</td>
<td>−0.57 (−0.048)</td>
<td>−2.08 (−0.173)</td>
<td>8.75 (0.728)</td>
</tr>
<tr>
<td>Three-day mean</td>
<td>−2.13 (−0.178)</td>
<td>−0.31 (−0.026)</td>
<td>−2.44 (−0.203)</td>
<td>8.77 (0.731)</td>
</tr>
</tbody>
</table>

Units are in g C m⁻² per day (mol m⁻² per day).

storage of CO₂. If the net ecosystem CO₂ uptake of the Pasoh forest is estimated as the total amount of three components (CO₂ flux, CO₂ storage and vertical mass flow), our results will indicate that this tropical forest functions as a CO₂ source.

There seems to be considerable errors in the estimation of the mass flow, since our values of the mass flow were too large, compared to other results. One of reasons for errors would be in the evaluation of the true vertical wind velocity from limited data set. Lee (1998) obtained the true mean vertical velocities from longer data sets (over 1.5 months). Our data set may be short for reliable estimations. Another error could arise from neglecting horizontal advection in Lee’s method. Finningan (1999) pointed out that horizontal advection cannot be neglected in most cases when we must bother with advective fluxes. Although the effect of horizontal advection might be large, we do not have a procedure for measuring it at a single-point observation. It is worth challenging to find how to evaluate effects of horizontal and vertical advections on NEE.

Acknowledgements

We thank the Forestry Department of Negeri Sembilan and the Director General of FRIM for granting us permission to work in the Pasoh Forest Reserve and Dr. K. Niiyama for providing his tree diameter data obtained in the forest reserve. The meteorological observations were carried out with the co-operation of the Hydrology Laboratory of FRIM. We would like to acknowledge the tremendous support received from Drs. Baharuddin Kasran, Zulkifli Yusop (present address: University of Technology Malaysia) and Azman Hassan, and the research assistants in the laboratory. This study was made as part of a joint research project between FRIM, UPM and NIES (Global Environmental Research Programme granted by the Japanese Environment Agency, Grant no. E-3).

References


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