

Measurement of methane flux over an evergreen coniferous forest canopy using a relaxed eddy
accumulation system with tuneable diode laser spectroscopy detection

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Abstract

Very few studies have conducted long-term observations of methane (CH_4) flux over forest canopies. In this study, we continuously measured CH_4 fluxes over an evergreen coniferous (Japanese cypress) forest canopy throughout 1 year, using a micrometeorological relaxed eddy accumulation (REA) system with tuneable diode laser spectroscopy (TDLS) detection. The Japanese cypress forest, which is a common forest type in warm-temperate Asian monsoon regions with a wet summer, switched seasonally between a sink and source of CH_4 probably because of competition by methanogens and methanotrophs, which are both influenced by soil conditions (e.g., soil temperature and soil moisture). At hourly to daily timescales, the CH_4 fluxes were sensitive to rainfall, probably because CH_4 emission increased and/or absorption decreased during and after rainfall. The observed canopy-scale fluxes showed complex behaviours beyond those expected from previous plot-scale measurements and the CH_4 fluxes changed from sink to source and *vice versa*.

1. Introduction

Most research on methane (CH_4) fluxes from natural ecosystems has focused on wetlands or rice paddy fields, which are thought to be large CH_4 sources and thus important components of the global CH_4 budget. Considering that a major portion of forest soil is water-unsaturated, forests are generally assumed

to be an insignificant atmospheric CH₄ sink, representing to about 6% of the global sink (Le Mer and Roger 2001). However, studies have revealed that forest ecosystems, especially in wet warm climates, are not always CH₄ sinks. For example, some upland soils could be a CH₄ source when soils become water-saturated following precipitation events (Silver et al. 1999; Savage et al. 1997; van den Pol-van Dasselaar et al. 1998). Wang and Bettany (1997) also reported that upland soils that were incubated anaerobically began producing CH₄ within days or weeks. However, the CH₄ dynamics in whole forest ecosystems are still poorly understood because of insufficient information on topographically complex landscapes. It is important to quantify CH₄ fluxes in forest ecosystems because they cover a large portion of continental areas.

Long-term CH₄ flux measurements in forested areas have been mostly performed using chamber methods. While chamber methods are useful for understanding the processes controlling CH₄ fluxes on small spatial scales (usually less than 1 m²), the small footprint of the measurement creates a difficult scaling problem (Denmead 1994) when estimating landscape-scale fluxes in heterogeneous terrain such as forests. Moreover, the occasional measurements of manual chambers restrict the time resolution. These inherent limitations of chamber methods have made it difficult to evaluate CH₄ dynamics in whole forest ecosystems, as CH₄ fluxes from forest soils have wide spatial and temporal variations. CH₄ fluxes in forest ecosystems could have wide-ranging spatio-temporal variations both emission and absorption sides, especially in the forest ecosystems which have wide spatio-temporal range in soil water status, such as

Asian monsoon forests under warm and humid climate, or boreal and tropical peat forests. Scaling up of CH₄ fluxes in those types of forests and understanding CH₄ dynamics as a whole ecosystem would be difficult only with chamber methods. In addition, both open and closed chambers disturb natural environmental conditions during the measurement by affecting airflow, radiant energy receipt, and energy transfer to the atmosphere (Denmead 1994). Consequently, CH₄ exchanges estimated by the chamber method could contain biases and uncertainties if up-scaled to stand, watershed, and regional scales.

Micrometeorological methods such as the eddy covariance (EC) method are ideally suited for continuous canopy-scale flux measurements integrated over a larger area without artificial disturbance. Although the EC method has been widely used for canopy-scale flux measurements, it has not been used until very recently for CH₄ measurements because it requires a fast-response and high-precision gas analyzer. Recent technological advances in the application of tuneable diode laser spectroscopy (TDLS) to *in situ* field measurements open the possibility of long-term EC measurement of CH₄ in a variety of ecosystems. Previously, a limited number of CH₄ EC measurements have been obtained in peatlands (Hendriks et al. 2008; Schrier-Uijl et al. 2009), rice paddy fields (Simpson et al. 1994), and prairies (Kim et al. 1998a, b). The lack of long-term CH₄ flux observations in forest ecosystems restricts our understanding of canopy-scale CH₄ dynamics. However, measuring CH₄ exchange over forest ecosystems is still challenging compared to measurements in the above source areas because of the small fluxes in forests (Smeets et al. 2009). According to previous EC measurements in wetlands and farmlands, the

precision of the CH₄ concentration measurements was 2.9 ppb at 10 Hz using a Quantum Cascade Laser Spectroscopy (QCLS) analyzer (QCL-TILDAS-76; Aerodyne Research Inc., Billerica MA, USA) (Kroon et al. 2007). Recently, the open path sensor is available for the CH₄ EC measurement with the precision of < 5 ppb at 10 Hz (McDermitt et al. 2011). However, those precisions are still insufficient to measure small CH₄ fluxes at forest ecosystems if the CH₄ fluxes measured by chamber techniques (Itoh et al. 2005, 2007, 2009) assumed to be representative to the canopy scale exchange.

Although the state-of-the-art CH₄ analyzers could be insufficient for the EC measurements, those analyzers are available for CH₄ flux measurements by using a micrometeorological relaxed eddy accumulation (REA) method (Businger and Oncley 1990; Hamotani et al. 1996, 2001). The REA method can take longer time for CH₄ concentration measurements, thus a laser signal can be averaged to optimize the instrumental sensitivity, and higher precision of TDLS CH₄ analyzer was achievable. The flux, calculated by the REA method, is equal to the difference in the mean concentrations of the trace gas of interest associated with updraft and downdraft, multiplied by the standard deviation of the vertical wind velocity and an empirical coefficient.

In this study, we employed an REA method (Businger and Oncley 1990; Hamotani et al. 1996, 2001) with a TDLS CH₄ analyzer for long-term observation of CH₄ fluxes from a temperate evergreen coniferous forest site. Our goal was to examine whether the REA method is applicable to (1) measure CH₄ fluxes over the forest canopy, (2) reveal the amplitude and seasonal variations in CH₄ fluxes, and (3)

examine the response of CH₄ fluxes to rainfall. This is the first report showing the seasonal cycle of canopy-scale CH₄ fluxes in a temperate forest.

2. Methods

2.1 Site description

The observations were made in a coniferous forest in the Kiryu Experimental Watershed, (KEW; area: 5.99 ha) in Shiga Prefecture, Japan. A meteorological observation tower is located in a small catchment within KEW (Fig. 1). The forest consists of 50-year-old Japanese cypress (*Chamaecyparis obtusa* Sieb. et Zucc.). Mean tree height was approximately 16.8 m in 2007. The annual mean air temperature and precipitation measured at the meteorological station shown in Fig. 1 from 2002 to 2009 were 13.3°C and 1,576 mm yr⁻¹, respectively. The site has a warm temperate monsoon climate with a wet summer. Rainfall occurs throughout the year with two peaks in summer due to the Asian monsoon; the early summer ‘Baiu’ front season and the late summer typhoon seasons. The entire watershed is underlain by weathered granite with considerable amounts of albite.

Canopy fluxes of heat, water, and CO₂ have also been measured at this site at 29-m above the ground, using the EC method (e.g., Takanashi et al. 2005; Kosugi et al. 2007; Kosugi and Katsuyama 2007; Ohkubo et al. 2007). Takanashi et al. (2005) reported that the CO₂ flux for 92% of the daytime flux and 81% of the nighttime flux originated from the forest area according to an analytical footprint model by

Schuepp et al. (1990). The trend in wind direction at this site did not change seasonally but had diurnal variations. The daytime wind direction was from all directions, whereas the night-time wind direction was mainly from the south (Kosugi et al. 2007). Some wetlands were located in riparian zones along streams within the flux footprint area, which were either always submerged or periodically submerged. The streams and the main wetland areas (approximately 10^0 - 10^2 m²) are shown in Fig. 1. The riparian zones and wetlands were distributed in both the north and south directions within the flux footprint area. The size of these areas could slightly increase after rainfall. Notably, an express highway was opened approximately 400 m south of the tower in February of 2008. During night-time, this highway was always inside of the flux footprint. The paddy fields were situated several km north to west of the tower, although these area were mostly out of the flux footprint (Takanashi et al. 2005). CH₄ fluxes from wetlands and water-unsaturated soils were investigated using a chamber method with a gas chromatograph analyzer (Itoh et al. 2005, 2007, 2009). Comparisons of the CH₄ fluxes from the previous chamber data and the present REA data will be described later.

2.2. Measurements

The CH₄ flux was measured using the REA method (Businger and Oncley 1990; Hamotani et al. 1996, 2001). Although the REA method is theoretically the same as the EC method, it does not require a fast response from the gas analyzer compared to the EC method. Compared to wetlands, forest canopies are

more challenging sites for conducting CH₄ flux measurements by the EC method. This is because the emission and absorption of CH₄ are both relatively small over forest canopies, and TDLS analyzers may not always be precise enough to detect the fluxes. The greatest benefit of applying the REA method is that sufficient precision in CH₄ concentration TDLS measurements is achievable by signal averaging over a longer duration. The precision of the TDLS CH₄ analyzer (FMA-200; Los Gatos Research, Mountain View, CA, USA) is 3 ppb at 10 Hz rate, 1 ppb at 1 Hz rate and 0.1 ppb at 100 s rate according to the catalog specifications. Moreover, the REA method can save electronic consumption and minimize the possible noises induced by the pressure drift of the measurement cell of the TDLS CH₄ analyzer, because the REA method with lower sampling frequency can measure CH₄ fluxes without a high-power vacuum pump. The another advantage of the REA method is that it does not require any corrections such as high frequency attenuation for closed-path EC method or WPL correction (Webb et al. 1980) for open-path EC methods, which could obscure the observed small flux values at the forest ecosystems. One possible disadvantage of the REA method involves the switching speed of the valve system, which may lead to the loss of high frequency information, however those effects can be negligible at measurements over tall forest canopies, such as in our forest (Ueyama et al. 2009). Equation 1 expresses CH₄ flux (F_{CH_4} , nmol m⁻² s⁻¹) (Subsequently, we use this abbreviation only for CH₄ flux measured by the REA method). This equation can also be used to calculate CO₂ flux (F_{CO_2} , μmol m⁻² s⁻¹):

$$F_{CH_4} = \sigma_w \left(\overline{S_{CH_4}^+} - \overline{S_{CH_4}^-} \right) \rho_a b \quad (1)$$

where σ_w is the standard deviation (SD) of the vertical wind velocity (w , m s^{-1}), $\overline{S_{CH_4}^+}$ and $\overline{S_{CH_4}^-}$ are the 30-minute mean CH_4 mole fractions (ppmv) associated with updraft and downdraft, respectively, and ρ_a (mol m^{-3}) is molar air density. The coefficient b was empirically determined from EC data using air temperature given by Eq. 2:

$$b = \frac{\overline{wT'}}{\sigma_w (\overline{T^+} - \overline{T^-})} \quad (2)$$

where $\overline{T^+}$ and $\overline{T^-}$ are 30-min mean fast-response temperature data associated with updraft and downdraft, respectively. We determined b to be 0.59, which is the average of 16,576 values obtained from Eq. 2 and the standard error was 0.04. The sensible heat flux and air temperature data used here was all data measured from August 2009 to August 2010 by the sonic anemometer (SAT-550; Kaijo Corp., Tokyo, Japan) mounted on top of the 29-m-tall tower. The term b was applied to both F_{CO_2} and F_{CH_4} . The value of b is relatively constant over a wide range of atmospheric stability (Bowling et al. 1998).

Our REA system consists of a sonic anemometer (SAT-550; Kaijo Corp.) to measure wind speed and direction, two diaphragm pumps (CV-201, Enomoto Co., Tokyo, Japan), four reservoirs (CCK-20; GL Science, Tokyo, Japan) to accumulate sampled gas, a $\text{CO}_2/\text{H}_2\text{O}$ gas analyzer (LI-840; Li-Cor Inc., Lincoln,

NE, USA), a CH₄ gas analyzer (Baer et al. 2002; Hendriks et al. 2008) (FMA-200; Los Gatos Research) and a data logger (CR1000; Campbell Scientific, Logan, UT, USA). The sonic anemometer was mounted on top of the 29-m-tall tower and the air inlets were set directly below the sonic anemometer. Air samples for updraft and downdraft were pulled through DK tubes (inner tube: 4 mm in diameter and coated with aluminium) to the reservoirs by two diaphragm pumps at a constant flow rate (0.7 l min⁻¹). The frequency of switching the pumps was 10 Hz. One pump worked only for updraft and the other worked only for downdraft. Updraft or downdraft was determined by the difference between the instantaneous and adjacent 15-min moving average of *w*. Air flow was switched using the solenoid valves (CKD USB3-6-3-E; CKD Corp., Aichi, Japan) and controlled by the CR1000 data logger. To sequentially determine the flux every half hour, we prepared two sets of sampling reservoirs: one pair of reservoirs accumulated air during 0–30 min and the other pair accumulated air for the next 30–60 min. After accumulating in the reservoirs for 30 min, the air in the reservoirs was pulled a diaphragm pump into the CH₄ analyzer at a flow rate of approximately 0.7 l min⁻¹, and the air in each reservoir was analyzed for 2 min. Three filters were inserted in the gas sample line to protect the CH₄ analyzer from dust and insects. Before entering the CO₂/H₂O and the CH₄ analyzers, the sampled air was dried using a gas dryer (PD-50T-48; Perma Pure Inc., Toms River, NJ, USA). Dilution by water vapour, which could not be completely removed by the drying system, was corrected for using the H₂O concentration measured with the CO₂/H₂O analyzer. We confirmed that the gas dryer did not alter the CH₄ mixing ratio within

measurement uncertainties. Data were recorded at 10 Hz by the CR1000 data logger and stored on a compact flash card using a compact flash module (CFM100, Campbell Scientific). A 10-s moving average filtered the high frequency noises for the CO₂/H₂O analyzer and a 1-s moving average was used for the CH₄ analyzer. Volumetric soil water content (VSWC) at a depth of 0–30 cm was measured with a CS616 water content reflectometer (Campbell Scientific) at four different points around the tower on the water-unsaturated forest floor, and soil temperatures were measured with a thermistor (RT-10,11,12; ESPEC Mic Corp., Kanagawa, Japan) at depths of 2 cm near the tower. Precipitation was measured with a tipping bucket rain gauge at an open screen site near the tower. Air temperature above the canopy was measured with a ventilated temperature and humidity sensor (HHP45AC; Vaisala, Helsinki, Finland) at a height of 29 m above the ground.

In this study, we compared CO₂ fluxes measured by the REA and EC methods in order to examine the validity of our REA system. An open-path CO₂/H₂O analyzer (LI-7500; Li-Cor) was used to measure CO₂ flux by the EC method. The double-rotation method was applied to the sonic anemometer velocities (McMillen 1988), and the Webb, Pearman, Leuning (WPL) correction for the effect of air density fluctuations (Webb et al. 1980) was applied to CO₂ flux using the EC method. Details of the EC measurements have been described by Kosugi et al. (2007) and Okubo et al. (2007b).

2.3. Data analysis

Hendriks et al. (2008) described the specifications of the CH₄ analyzer used in this study in detail. To examine the accuracy and precision of our CH₄ analyzer, calibration experiments were performed on site using a standard CH₄ gas cylinder (Takachiho, Tokyo, Japan, 1773 ppb CH₄ in synthetic air) several times during the course of this study. The typical SD for determining the CH₄ mixing ratio was 0.4 ppb with a 30-s moving average within a 3-min standard gas flow period, which is the same condition used for calculating the reservoirs concentrations with the REA method; the reservoir concentrations were averaged for 30 s and analyzed within 2 min. No significant drift in the measurement accuracy of the CH₄ analyzer was observed during the entire observation period (less than 6 ppb). We also examined the detection limit of CO₂ and CH₄ fluxes in our REA system by storing the same air in reservoir pairs and measuring the concentration difference in each pair. This check mode was performed during 1 day of every month.

We performed a *t*-test (significance level: 0.05) for the CH₄ concentration difference between updraft and downdraft to examine whether there was a statistical difference between the mean values. F_{CH_4} assumed to be zero by the *t*-test (21.8% of all available data) is shown as grey circles in Figs. 3 and 5. All CO₂ and CH₄ fluxes collected with the REA method were rejected when CO₂ flux data collected with the EC method did not meet the stationary criteria (Foken and Wichur 1996; Aubinet et al. 2000). We also rejected CO₂ and CH₄ fluxes collected during night-time under highly stratified conditions, using a previously examined friction velocity threshold of 0.3 m s⁻¹ for the CO₂ flux data (Takanashi et al. 2005).

The total amount of F_{CH_4} data rejected by these criteria accounted for 66% of the entire data series.

The data analyzed in this study were recorded between 1 August 2009 and 31 August 2010. Data were missing from 11 to 20 August 2009, from 16 June to 22 July 2010, and from 10 December 2009 to 17 February 2010 due to instrumental malfunctions.

3. Results

3.1. Validity of the CH_4 fluxes collected with the REA system

Before application to F_{CH_4} measurement, we validated our REA system by comparing F_{CO_2} measured by the EC and REA method for daytime (Fig. 2a) and nighttime periods (Fig. 2b). The CO_2 fluxes by the EC and REA methods were highly correlated for both daytime with a slope of 0.95, $r^2 = 0.72$ and the root mean square error (RMSE) of $3.7 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 2a) and nighttime with a slope of 0.81, $r^2 = 0.45$ and the RMSE of $3.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 2b). Although the slopes of the linear regression showed a slightly smaller value than 1.0, the observed data both in the daytime and nighttime were mostly scattered around the 1:1 line and the F_{CO_2} measured by the REA method did not show obviously higher or lower values than those by the EC method (Fig. 2a, b). The F_{CO_2} measured by the EC and the REA methods had worse correlation in the night-time than daytime (Fig. 2b).

The F_{CH_4} detection limit obtained from the check mode with our REA system showed a diurnal variation because it depended on turbulent intensity (i.e., σ_w in Eq. 1 is larger in the daytime than in the

night-time) The night-time (0:00–6:00 and 18:00–24:00) and daytime (6:00–18:00) F_{CH_4} detection limits averaged for all 14 check mode days were 4.2 ± 3.7 and $7.4 \pm 5.9 \text{ nmol m}^{-2} \text{ s}^{-1}$, respectively, and the detection limits did not change seasonally.

3.2. Amplitude and seasonal variations in CH_4 flux and its response to rainfall

Figure. 3 shows the seasonal variations in (a) instantaneous F_{CH_4} , (b) air and soil temperature, and (c) precipitation and VSWC. The average and SD of F_{CH_4} was $5.9 \pm 11.5 \text{ nmol m}^{-2} \text{ s}^{-1}$ for the summer of 2009 (August and September), $5.3 \pm 10.4 \text{ nmol m}^{-2} \text{ s}^{-1}$ for the fall of 2009 (October and November), $2.2 \pm 10.9 \text{ nmol m}^{-2} \text{ s}^{-1}$ for the winter of 2009 (December, February, and March), $-10.0 \pm 14.3 \text{ nmol m}^{-2} \text{ s}^{-1}$ for the spring of 2010 (April, May, and June), and $-4.7 \pm 15.3 \text{ nmol m}^{-2} \text{ s}^{-1}$ for the summer of 2010 (July and August). This site had a heterogeneous topography, and some riparian zones and wetlands were distributed both in the north and south directions within the flux footprint area. However, the wind direction at this site did not change seasonally. We confirmed that both daytime and night-time F_{CH_4} from the north or south was not particularly larger than those from other wind directions by analysing F_{CH_4} for each wind direction (Fig. 4). F_{CH_4} seasonally shifted from emission in the summer and fall of 2009 to absorption in the spring of 2010. Then the absorption weakened and changed to emission in the summer of 2010 (Fig. 3a). The diurnal patterns changed seasonally. In the summer and fall of 2009, F_{CH_4} showed clear diurnal variation with an emission peak around noon (Figs. 5a, b and 6a, b). Large emission was

observed in the fall of 2009 during sequential rain events for several days (Fig. 5b). The emission decreased with a decrease in air temperature (Fig. 6a, b), and then F_{CH_4} became almost zero in winter (Figs. 5c and 6c). F_{CH_4} remained relatively small until the spring of 2010 (Fig. 5d). Then, F_{CH_4} gradually shifted to exhibit a clear diurnal variation with an absorption peak around noon, which was an opposite pattern compared to the previous summer (Fig. 5e and 6d). The magnitude of peak CH_4 absorption increased with air temperature. Maximum CH_4 absorption was observed in June, when the absence of rain lasted 17 days and VSWC decreased. After intense rainfalls in late July 2010, the CH_4 absorption rate gradually decreased and seemed to shift to emission.

We detected evidence for short-term F_{CH_4} that rainfall was an important factor contributing to increased CH_4 emission. After rainfall on 12 September 2009, high F_{CH_4} was observed on 13 September 2009 (Fig. 5a) and similarly on 27 October and 2 November 2009 (Fig. 5b). Averaged diurnal variations for the summer of 2009 (August and September) and the fall of 2009 (October and November) also showed that CH_4 emission increased after precipitation (Fig. 6a, b). Even when high CH_4 absorption rates were observed around noon, rainfall contributed to weakening CH_4 absorption and/or F_{CH_4} switched to emission as shown on 24 May 2010 (Fig. 5e). Averaged diurnal variation for the spring of 2010 (April, May, and June) also showed that CH_4 absorption was weakened after precipitation (Fig. 6d). Approximately a day after rainfall, CH_4 emission typically increased and/or absorption decreased (Fig. 5a, b, e). The response of F_{CH_4} to rainfall was not obvious in winter (Figs. 5c and 6c).

4. Discussion

4.1. Assignment of the REA system

From comparison of CO₂ fluxes between the REA and EC data, we concluded that our REA system generally provided a good approximation of the EC method and could thus be applied to measure F_{CH_4} . One possible reason for the difference in CO₂ fluxes between the EC and REA methods is the method for determining coefficient b in Eq. (1); coefficient b , although constant in Eq. 1, changes slightly and is not constant throughout the day or year. Another possibility is that the loss of high frequency information due to the switching speed of the REA valve system might lead to an underestimation of F_{CO_2} with the REA method. However, the latter possibility was thought to be less likely because turbulent transfer was significant at a lower frequency below 1 Hz at this site (Kosugi et al. 2007; Ueyama et al. 2009).

The most difficult part of measuring F_{CH_4} in the forest canopy is that the F_{CH_4} detection limit is very close to the actual flux range. Although F_{CH_4} was larger than the detection limit in summer, fall, and spring, it was smaller in winter. Chamber studies revealed that F_{CH_4} ranged from approximately 0 to 720 nmol m⁻² s⁻¹ in wetlands and from -1.7 to 1.4 nmol m⁻² s⁻¹ in water-unsaturated forest floors (Itoh et al. 2005, 2007, 2009); some of these values are smaller than the detection limit of our REA system. We suggest that further improvements in measurement precision for the difference between upward and downward air CH₄ concentration are required to measure F_{CH_4} more precisely particularly in the winter. A

possible approach to improving the precision of our REA system is to apply the hyperbolic REA method (Bowling et al. 1999), which samples air only for high turbulent transport eddies. Applying this method would allow us to increase the CH_4 concentration differences (up to a factor of 2.7; Bowling et al. 1999) and thus improve the precision of the REA system. One disadvantage of the hyperbolic REA is that the majority of air (80%) is discarded, and roughly 10% of the original volume is sampled into each of the updraft and downdraft reservoirs (Bowling et al. 2003). The information contained in the discarded air must be reconstructed through the coefficient b . The b is determined under the assumption of the scalar similarity between temperature, CO_2 and CH_4 , so under some conditions large errors can result from violation of scalar similarity using the hyperbolic REA (Ruppert 2002).

4.2. Amplitude and seasonal variations in CH_4 flux and its response to rainfall

At the study site, the main CH_4 sources areas (riparian wetlands) were heterogeneously distributed within the flux footprint area, as shown in Fig. 1, and the typical wind direction (described in Section 2.1) did not change seasonally. Although there were large CH_4 sources in the north and south, daytime and night-time F_{CH_4} from the north or south were not particularly larger than those from other wind directions (Fig. 4). Although there was a difference between the F_{CH_4} from the north and south in summer 2010, this was probably caused by artificial difference due to limited number of available data; F_{CH_4} in summer 2010 could not be affected by wind direction. Thus, we assumed that the observed F_{CH_4} seasonal

variations would be mainly caused by the activity of methanogens and methanotrophs influenced by the soil temperature and water conditions but not wind direction.

Itoh et al. (2005, 2007, 2009) measured seasonal CH₄ flux variations from different parts of the slope in a water-unsaturated forest floor and riparian wetlands at the study site using the chamber method from 2001 to 2005. They showed that CH₄ emission rates from wetlands ranged from 0 to 720 nmol m⁻² s⁻¹, and that the emission rates increased significantly during high soil temperature and VSWC periods. They hypothesised that the emission rates were large enough to turn the entire watershed into a net CH₄ source, even though the source areas were very limited (Itoh et al. 2005). The emission rates from the wetlands varied from year to year due to the hydrological conditions that changed in relation to precipitation patterns (particularly summer precipitation patterns) (Itoh et al. 2007). The reported CH₄ fluxes from the water-unsaturated forest floor at this site ranged from -1.7 to 1.4 nmol m⁻² s⁻¹ (Itoh et al. 2009). CH₄ uptake was usually observed throughout the sampling periods; however, on lower hillslopes, where groundwater constantly existed underground, weak CH₄ uptake was observed only at low soil temperature (< 15°C); these areas turned to a CH₄ source at high soil temperatures (Itoh et al. 2009). The chamber measurements revealed that CH₄ fluxes in this forest were heterogeneous at both temporal and spatial scales, thus highlighting the importance of conducting continuous measurements of canopy-scale CH₄ fluxes integrated over a larger area to evaluate the total CH₄ budget.

Four new insights were obtained by combining the results from earlier chamber studies and this study.

First, the canopy-scale F_{CH_4} results by the REA method showed emission in the summer and fall of 2009, indicating that a forest ecosystem consisting mostly of a water-unsaturated forest floor could be a CH_4 source for an entire watershed, possibly due to a large source contribution by a tiny wetland (Whalen et al. 1990; Keller and Reiners 1994; Hudgens and Yavitt et al. 1997; Itoh et al. 2007). Another possible source was the contribution from the lower hillslopes of the water-unsaturated forest floor. Even though the soil surface was water-unsaturated, groundwater constantly existed underground and produced CH_4 under anaerobic conditions, which could have been emitted (Itoh et al. 2009). This study shows, for an entire watershed, that a Japanese cypress forest in a warm temperate climate could be a CH_4 source in summer and fall according to tower based measurements. Previous chamber-based studies speculated on the canopy-scale CH_4 dynamics from the plot-scale measurements, which might contain large uncertainties. Our canopy-scale measurements support the results of earlier chamber measurements. We found that monthly averaged F_{CH_4} in October of 2009 was $6.6 \text{ nmol m}^{-2} \text{ s}^{-1}$ and it was not far less than the average CH_4 fluxes in a peat meadow ($29.7 \text{ nmol m}^{-2} \text{ s}^{-1}$, Hendriks et al. 2008), a dairy farm ($42.7 \text{ nmol m}^{-2} \text{ s}^{-1}$, Kroon et al. 2007) and a boreal fen ($80 \text{ nmol m}^{-2} \text{ s}^{-1}$, Long et al. 2010). It is not negligible CH_4 emission from forest ecosystems, and it is important to quantify CH_4 fluxes in forest ecosystems and monitor it in the long-term.

Second, continuous measurements at high temporal resolution revealed that the canopy-scale CH_4 emissions increased and/or absorption decreased after rainfall particularly in summer and fall of 2009.

The F_{CH_4} response to rainfall was caused by changes in the soil water condition because the methanogenic activities increase and methanotrophic activities decrease in anoxic environments (Le Mer and Roger 2001). The area of the CH_4 source was broadened along the riparian zones after rainfall, and the lower hillslope part of the water-unsaturated forest floor may have switched from a sink to a source for CH_4 because the anaerobic area may also have broadened deep underground, as mentioned above. Another possibility is that CH_4 diffusion from the air to the soil may have been inhibited by rainfall causing a decline in CH_4 absorption (Bradford et al. 2001). As shown in Fig. 5a, b, e, the influence of rainfall to F_{CH_4} was obvious 1 or 2 days after rainfall events, at the short time-scale. On the other hand, F_{CH_4} tended to be influenced by rainfall in the seasonal time-scale as seen in the shift of F_{CH_4} to emission during summer 2010 (Fig. 3a). F_{CH_4} seemed to shift from absorption to emission during about 2 weeks after intense rainfalls in late July 2010 (Fig. 3a). These different time-scale responses of F_{CH_4} to rainfall were probably caused by different processes, and should be investigated with more data. In winter, the response of F_{CH_4} to rainfall appeared to be low, suggesting that less CH_4 was produced and/or absorbed in winter compared to other seasons; the activities of both methanogens and methanotrophs are low at low soil temperatures, although methanotrophs are much less temperature dependent (Dunfield et al. 1993).

Third, CH_4 absorption rates increased from spring 2010 as soil temperatures increased and VSWC decreased. These results are consistent with previous chamber measurements (Itoh et al. 2009). Uptake rates increased as soil temperature increased in the lower range of temperature ($<15^{\circ}C$) and as VSWC

decreased. Previous studies reported a similar activation of methanotrophs with an increase in temperature (Whalen et al. 1990; Dobbie et al. 1996; Prime and Christensen 1997; Ishizuka et al. 2000). In contrast, methanogens function at intermediate temperature ranges from 20 to 40°C (Yamane et al. 1961), and their activity is extremely low at low temperatures (Dunfield et al. 1993). The large F_{CH_4} absorption obtained in the spring of 2010 by the REA method was possibly due to the different responses of methanogens and methanotrophs to temperature. Methanotrophs might function well under conditions where methanogens are still unable to function well (i.e., low temperature) (Dunfield et al. 1993; La Mer and Roger 2001). We still do not have enough information to explain the differences in F_{CH_4} between fall 2009 and spring 2010 within a similar temperature range. These differences represent complex behaviour beyond that expected on the basis of previous plot-scale measurements. The difference in temperature before the sampling season (summer or winter in this case) might have affected both methanogenic and methanotrophic activities during these periods. Longer duration observational data are needed to help clarify the seasonal F_{CH_4} variation in forest ecosystems.

Finally, the CH_4 absorption rates in spring 2010 (monthly averaged F_{CH_4} from April to June of 2010 ranged from -5.1 to -18.3 $\text{nmol m}^{-2} \text{s}^{-1}$) were larger than those reported by the previous chamber study (-1.7 to 1.4 $\text{nmol m}^{-2} \text{s}^{-1}$; Itoh et al. 2009) at the water-unsaturated forest floor at this site. Although the CH_4 fluxes obtained by the REA and chamber measurements cannot be compared directly, one possible explanation involves the detection limit of our REA system ($4.2 \pm 3.7 \text{ nmol m}^{-2} \text{s}^{-1}$ in the night-time and

7.4 ± 5.9 nmol m⁻² s⁻¹ in the daytime), which may not be sufficient to detect the range of CH₄ uptake rates obtained by the chamber method for the water-unsaturated forest floor (-1.7 to 1.4 nmol m⁻² s⁻¹). The other possible reason is that the chamber method is not always an excellent tool for investigating representative CH₄ flux over a large watershed. An unobserved area that is consuming CH₄ more effectively than estimated previously might exist at the study site. Recently, we have been conducting continuous chamber measurements of CH₄ flux using the same TDLS CH₄ analyzer at the water-unsaturated forest floor at the study site and have found several times higher CH₄ absorption rates than the earlier chamber measurements at one of three automated chambers (unpublished data). These results suggest that canopy-scale measurements using micrometeorological methods are important to evaluate total CH₄ exchange and its impact on the environment.

Conclusions

This study is the first report of continuous measurements of canopy-scale F_{CH_4} in an upland forest using the REA method with a TDLS CH₄ analyzer. Our observations revealed how the entire forest ecosystem complexly switched between being a CH₄ sink or a source on hourly, diurnal, and seasonal scales. As micrometeorological methods provide spatially integrated fluxes with high temporal resolutions, measuring F_{CH_4} with these methods is particularly important to investigate the CH₄ dynamics in forest ecosystems. In this study, we demonstrated that the REA method is applicable for measuring

CH₄ flux over a large representative area. Further longer-term observations with improvement of the system are needed to evaluate the controlling factors for methanogens and methanotrophs activity in the CH₄ dynamics of forest ecosystems. A combined approach between conventional chamber and micrometeorological methods is particularly important to evaluate the total CH₄ exchange, its impact on the environment, and the detailed processes involved.

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Figure captions

Figure 1 Topographic map of the observation site. Precipitation was recorded at the indicated meteorological station. The streams are shown as bold lines, and riparian zones are located along the streams. The main wetland areas are in black.

Figure 2 Comparison between CO₂ fluxes obtained by the REA and EC methods at the half-hourly time scale in the **a** daytime (0600-1800 h) and **b** nighttime (0000-0600 and 1800-2400 h). The thin and bold lines represent 1:1 and linear regression, respectively. The linear regression equation and r^2 obtained from analysis of all data are shown.

Figure 3 Seasonal variation in **a** instantaneous canopy CH₄ flux and CH₄ flux assumed to be zero by the *t*-test (grey circles), **b** air temperature and soil temperature (grey lines), and **c** precipitation and the volumetric soil water content (VSWC) at the water-unsaturated forest floor during August 2009 and August 2010, in an evergreen Japanese cypress forest in a warm temperature climate.

Figure 4 Daytime and night-time CH₄ fluxes averaged for each wind direction (north, south, east, west) in each season: **a** the sum of all seasons, **b** summer 2009, **c** fall 2009, **d** winter 2009, **e** spring 2010, and **f** summer 2010 are shown. Daytime and night-time CH₄ fluxes are shown as white and black circles. Error bars show the standard deviations. The data used for averaging seasonal CH₄ fluxes for each wind direction are shown as bars. The data for daytime and night-time are shown as white and black bars, respectively.

Figure 5 Diurnal course of instantaneous canopy CH₄ flux and CH₄ flux assumed to be zero by the *t*-test (grey circles), precipitation, and air temperature and soil temperature (dotted lines) measured in **a** summer (between 5 September and 14 September 2009), **b** fall (between 25 October and 3 November 2009), **c** winter (between 4 December and 8 December 2009 and between 7 March and 11 March 2010), **d** early spring (between 1 March and 5 March 2010), and **e** late spring (between 21 May and 30 May 2010) in an evergreen Japanese cypress forest in a warm temperature climate.

Figure 6 Diurnal variations of CH₄ fluxes before precipitation (black circle) and after precipitation (white

circle) (in case accumulated precipitation was more than 2 mm half hour⁻¹) and air temperature, averaged for **a** the summer of 2009 (August and September), **b** the fall of 2009 (October and November), **c** the winter of 2009 (December, February and March), and **d** the spring of 2010 (April, May and June). Before and after precipitation were discriminated according to accumulated precipitation within 24 h was more than 2 mm half hour⁻¹ or not. Error bars show the standard deviations for CH₄ fluxes.

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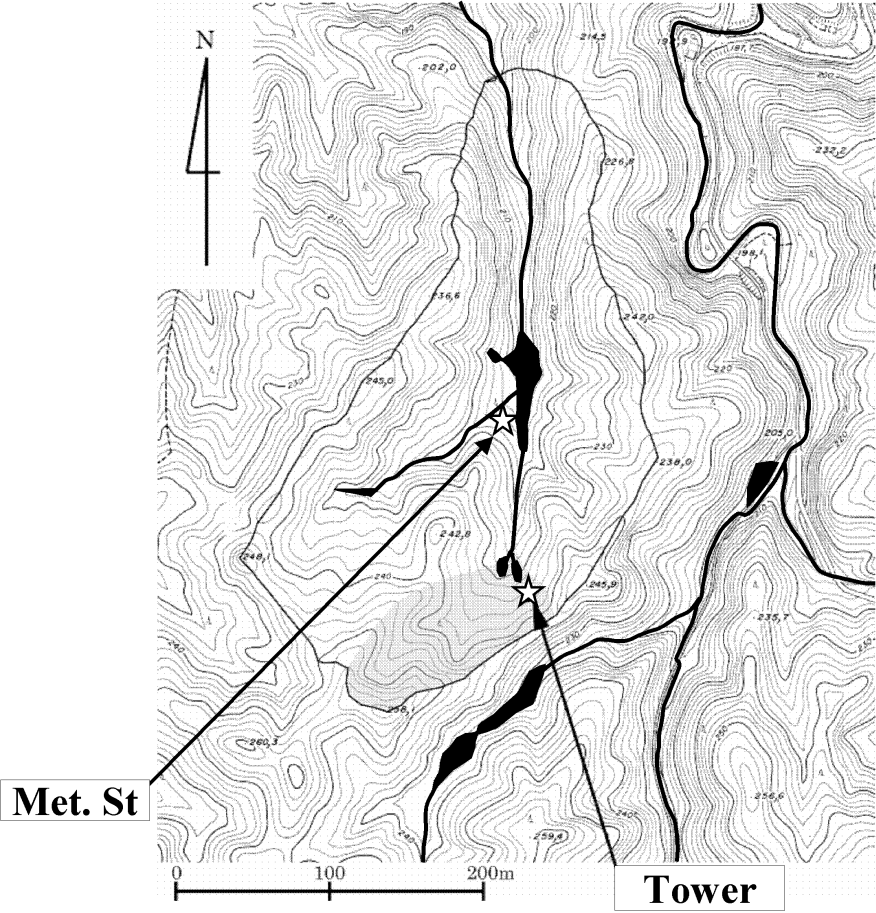
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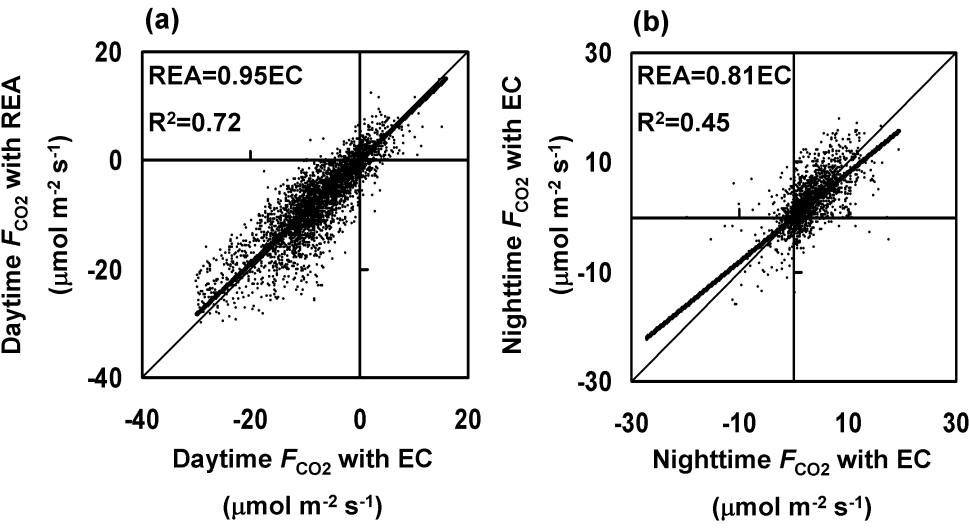
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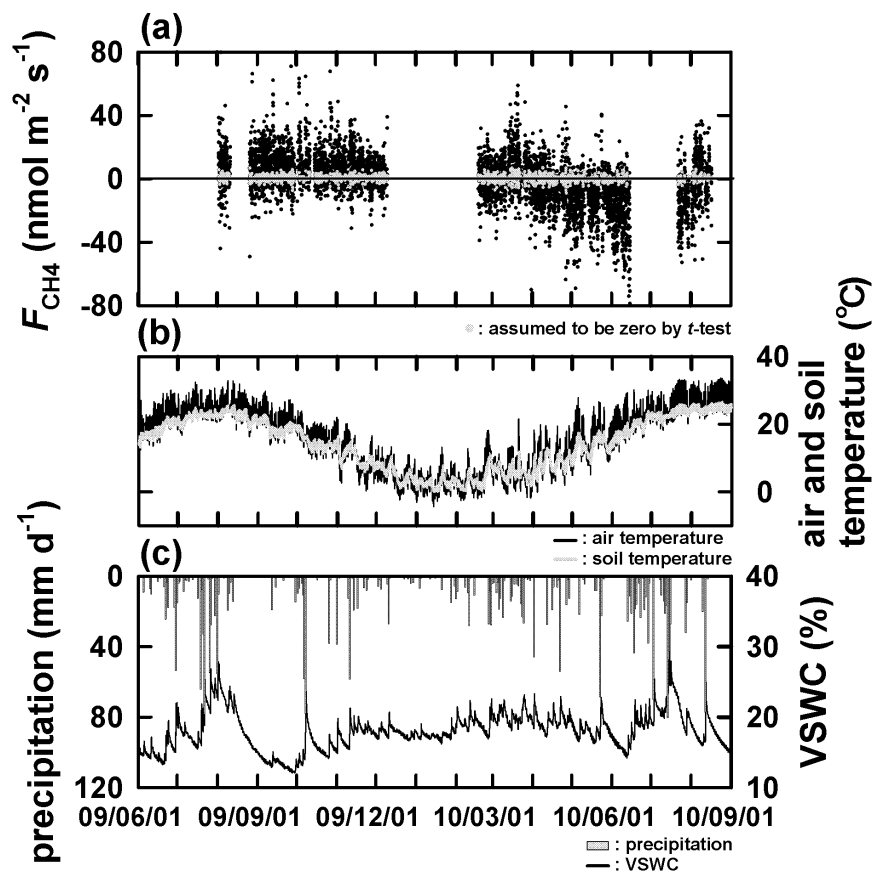
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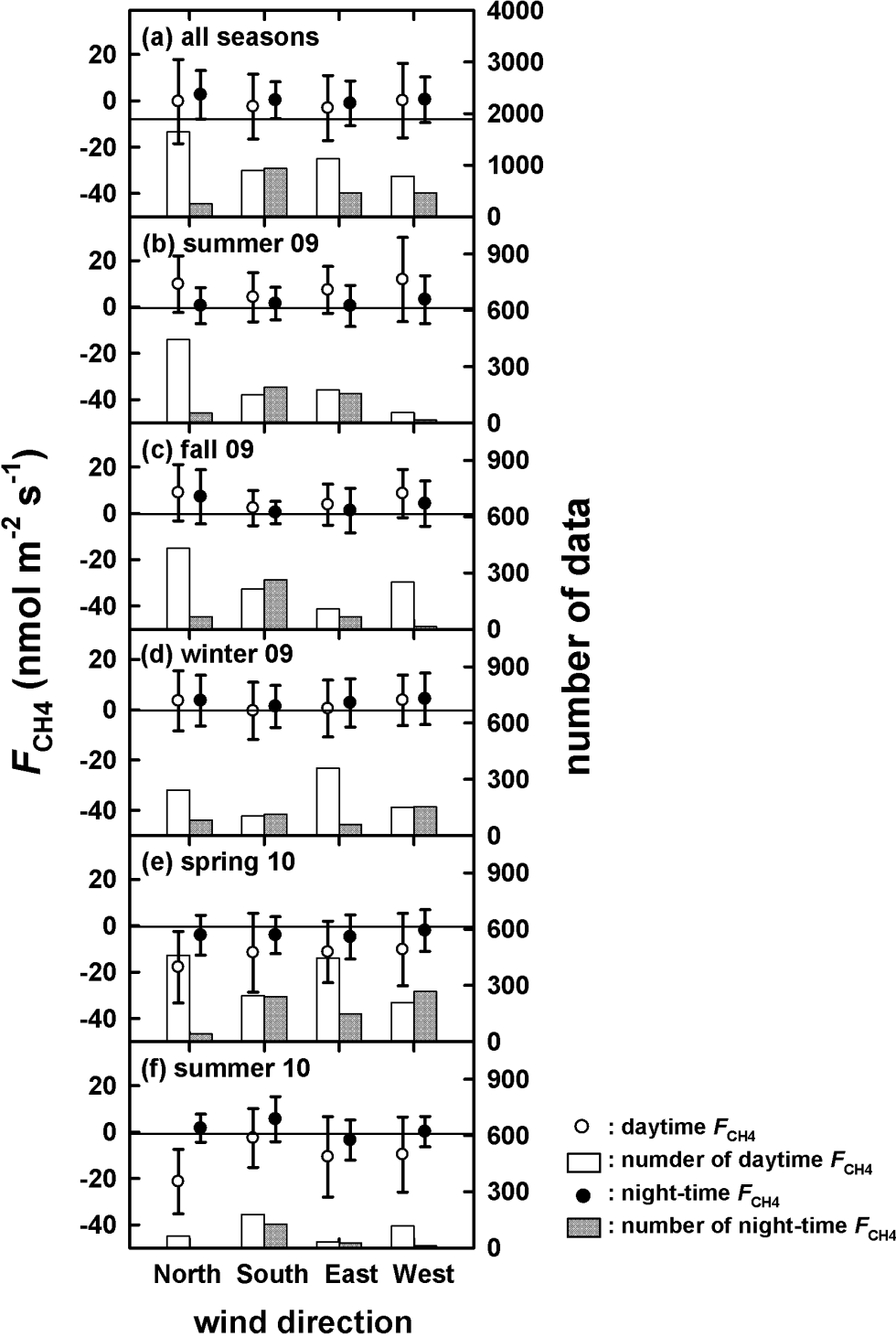
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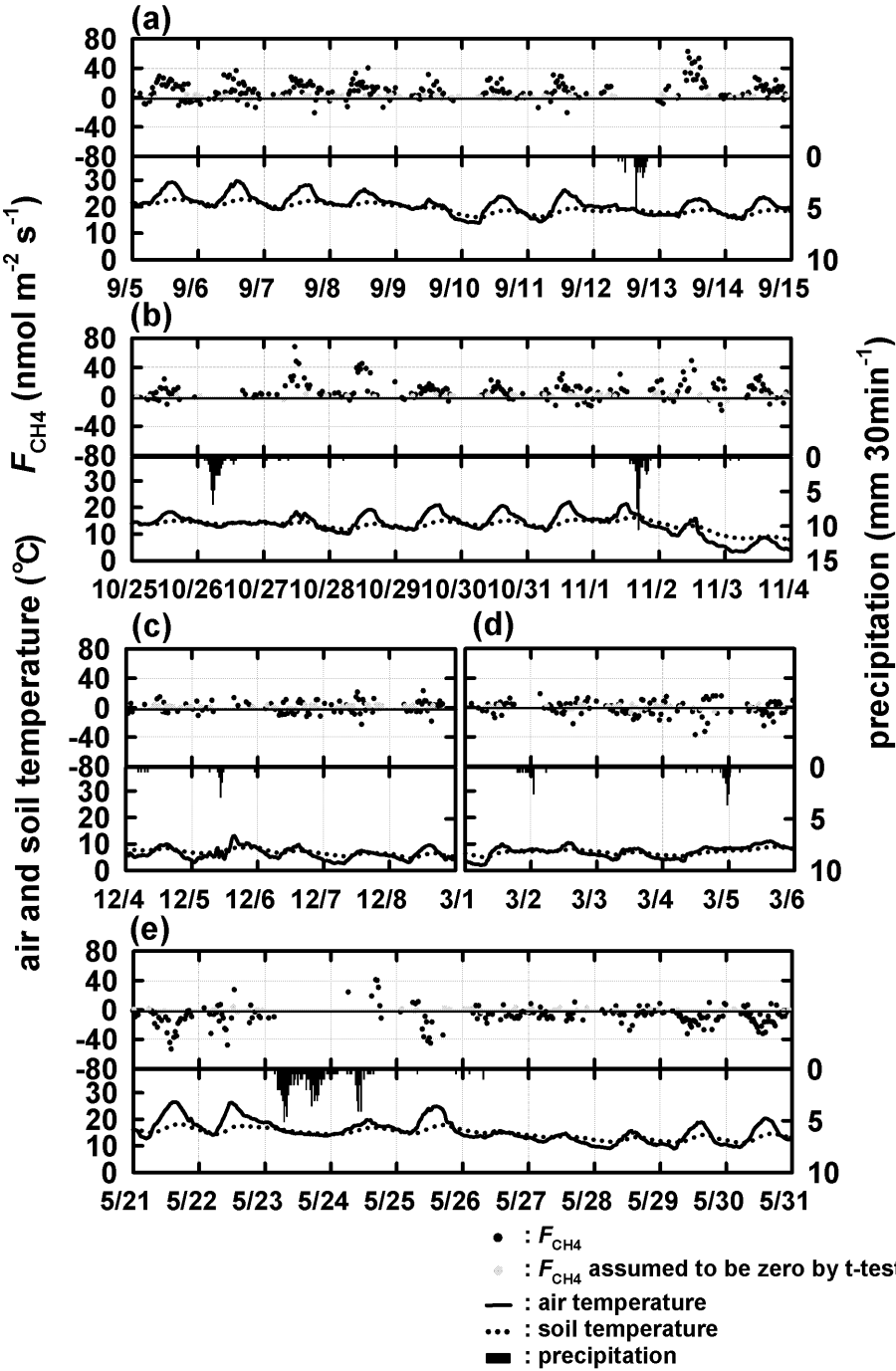
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