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Exploring sub-daily to seasonal variations in methane exchange in a single-crop rice paddy in central Japan

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ABSTRACT

Season-long methane (CH_4) exchange was observed in a rice paddy field in central Japan (Kanto Region) using the eddy covariance technique to clarify the variations in environmental controls on CH_4 exchange in different stages of cultivation. Before heading of rice plant, the CH_4 emission depended on wind speed and soil temperature. The soil temperature dependence can be due to an increase in CH_4 production, higher molecular diffusion, and higher conductance within rice plant at higher soil temperature. An occurrence of ebullitive emission was also suggested from the wind speed dependence. After heading was completed, relative humidity and water temperature influenced CH_4 emission. The amplitude of the diurnal variation in emission increased from 0.03 μmol m^{-2} s^{-1} in the late pre-heading stage to 0.13 μmol m^{-2} s^{-1} in the post-heading stage. Induced convective throughflow within the rice aerenchyma after the change in plant structure was attributable to this variation in environmental controls after the heading. After drainage, CH_4 emission was confined to short periods after strong rain events. The water level controlled the timing of emission, most likely by influencing the diffusion efficiency from the anoxic soil to the atmosphere and CH_4 oxidation in the surface oxic zone. The variation in the dominant transport pathway needs to be accounted for in terrestrial ecosystem models to accurately predict CH_4 emission from rice paddies.

1. Introduction

Methane (CH_4) is an important greenhouse gas, accounting for about 20% of the total direct radiative forcing from long-lived greenhouse gases since pre-industrial times (Forster et al., 2007). Rice paddy fields are a major source of CH_4. Many studies have investigated the source strength and environmental controls on CH_4 exchange in rice paddies using the chamber technique (Cicerone and Shetter, 1981; Holzapfel-Pschorn and Seiler, 1986; Denier van der Gon and Neue, 1995; Nishimura et al., 2004; Tokida et al., 2013; Weller et al., 2015), pot experiments (Hosono and Nouchi, 1997b; Chidthaisong and Watanabe, 1997b; Watanabe et al., 1999) and micrometeorological observations (Simpson et al., 1995; Miyata et al., 2000; McMillan et al., 2007; Meijide et al., 2011; Hatala et al., 2012a, b; Alberto et al., 2014). Methane emissions from rice paddies at the global scale have also been estimated from terrestrial ecosystem models (Ito and Inatomi, 2012; Zhang et al., 2016) and atmospheric inversions (Fung et al., 1991; Hein et al., 1997; Frankenberg et al., 2005; Chen and Prinn, 2006).

Despite these efforts, there is still large uncertainty regarding the global CH_4 emissions from rice paddies (Kirschke et al., 2013; Zhang et al., 2016). This stems in part from the poor representation of CH_4 exchange processes in terrestrial ecosystem models. Thus, it is necessary to improve terrestrial ecosystem models for CH_4 emissions. To model the CH_4 exchange at the atmosphere–rice paddy interface, in addition to CH_4 production, it is important to understand the transport pathways from the anoxic soil where CH_4 is produced to the atmosphere, as well as the environmental controls on the transport processes. In general, there are three main transport pathways in wetlands (Schlesinger and Bernhardt, 2013): molecular and turbulent diffusion through the flooded water layer, ebullition, and plant-mediated transport, which includes both molecular diffusion and active convective throughflow (Dacey, 1980; Brix, 1988; Armstrong and Armstrong, 1990; Schütz et al., 1991; Hosono and Nouchi, 1997b).

For rice paddies, plant-mediated transport via molecular diffusion

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(Denier van der Gon and van Breemen, 1993) was found to be the dominant transport pathway (Cicerone and Shetter, 1981; Holzapfel-Pschorn et al., 1986; Schütz et al., 1989b; Butterbach-Bahl et al., 1997). These studies also found that the contribution from ebullition was significant only in the early cultivation stage. In addition, Nouchi et al. (1994), Hosono and Nouchi (1997b) and Chanton et al. (1997) suggested the existence of convective throughflow for rice plants. Recent chamber studies (Minamikawa et al., 2012; Tokida et al., 2014) have shown that the amplitude of the diurnal cycle of CH_4 emission increased after heading, implying that the dominant transport pathways can vary depending on the stage of cultivation. These studies suggest the need to examine the dominant environmental factors controlling the CH_4 emission in the different stages of cultivation for rice paddies, because different transport pathways can be influenced by different environmental factors.

Environmental controls on CH_4 emission from wetlands have been reported in the literature. Many researches (e.g., Holzapfel-Pschorn and Seiler, 1986; Schütz et al., 1989a; Sass et al., 1991; Khalil et al., 1998) reported that CH_4 emission was controlled by soil temperature. A higher temperature results in higher CH_4 production and higher molecular diffusivity, and therefore a higher CH_4 diffusion to the atmosphere through the soil and water layers and plant aerenchyma. In addition, Hosono and Nouchi (1997a) found that conductance through rice plant for CH_4 transport was positively correlated with temperature in the rhizosphere. Hatala et al. (2012a) found that the diurnal variation of CH_4 emissions was correlated with the variation of gross ecosystem photosynthesis in a rice paddy, suggesting the importance of a carbon supply from the root as a control on CH_4 emissions. Convective throughflow has been studied mainly for wetland plants, and it is driven by pressure differential caused by humidity-induced pressurization and thermal transpiration mechanisms (Dacey, 1980; Armstrong and Armstrong, 1990). Humidity-induced pressurization and convective throughflow were reported to be enhanced under high temperature and low relative humidity in the ambient air and high radiation (Armstrong and Armstrong, 1991; Brix et al., 1992). Thermal transpiration is enhanced when temperature difference between plant and ambient air becomes large (Schröder et al., 1986). High solar radiation can result in high leaf temperature and high water vapor concentration in the air space within plant, thus it may affect the both pressurization mechanisms (Armstrong and Armstrong, 1991). Ebullition from wetlands and lakes is known to be triggered by lowering of atmospheric pressure (Martens and Klump, 1980; Tokida et al., 2007) and wind speed (Keller and Stallard, 1994; Joyce and Jewell, 2003).

Continuous observations with micrometeorological techniques such as eddy covariance can provide data suitable to examine the variations of environmental controls on ecosystem-scale CH_4 emissions, and also to validate terrestrial ecosystem models. For example, in *Phragmites*-dominated wetlands, an enhancement of CH_4 emissions after plant tillering has been reported, and was related to solar radiation (Kim et al., 1998; van den Berg et al., 2016). Kim et al. (1998) suggested that the enhancement was due to an occurrence of convective throughflow in the plant.

We applied the eddy covariance technique to observe ecosystem-scale CH_4 exchange in a rice paddy field in central Japan (Kanto Region) in both the growing and post-harvest seasons. Our objectives were: 1) to clarify the environmental controls on ecosystem-scale CH_4 exchange to infer the main transport pathways for the different stages of cultivation, and 2) to quantify the total annual CH_4 exchange in the rice paddy field.

2. Observations and data analyses

2.1. Study site

Data were obtained from the Mase rice paddy site (36°03′N, 140°02′E, 12 m a.s.l.) in Tsukuba, Japan in 2012. The site is one of the AsiaFlux monitoring sites, and energy and CO_2 fluxes have been continuously observed using the eddy covariance technique (Miyata et al., 2005; Saito et al., 2005; Mano et al., 2007a, b; Ono et al., 2008b, a, 2013). The paddy field was cultivated with a single rice crop (*Oryza sativa* L. ssp. *japonica* cv. Koshihikari). Paddy fields with similar cultivation practices extend for at least 1 km in the direction of the prevailing wind. The soil was a grey lowland paddy soil, with a light-clay texture (a Typic Endoaquept; Soil Survey Staff, 2006). The annual mean air temperature is 13.5 °C and annual precipitation is 1235.6 mm based on observations made at the Tateno Observatory of the Japanese Meteorological Agency (9 km east of the Mase site). Other site details can be found in Han et al. (2005), Saito et al. (2007), Hayashi et al. (2012), Iwata et al. (2014), and Ikawa et al. (2017).

The field was plowed on April 10, 2012 before the start of irrigation. Irrigation started on April 25 and the field was flooded until August 28, except for a temporary drainage during June 24–28. Rice seedlings were transplanted with a mean density of 14.51 hills m^{-2} on May 2. Heading started on July 27 and was completed on July 30. The crop was harvested on September 12. After harvesting, the field was plowed on October 6 and left fallow for seven months until transplantation in the following year. Poultry manure was added at 278 kg ha^{-1} (69.5 kgC ha^{-1}) on February 22, and one-shot basal fertilizer (N, P, K = 55.5 kg ha^{-1}) was added on April 8. In this paddy field, the residual of the rice straw after harvesting was burnt or removed from the field depending on the different years, which determined the amount of labile carbon in the soil and, in turn, affected the magnitude of CH_4 emissions (Mano et al., in preparation). In the previous year, the residual was burnt on September 19, 2011, and in the year of observation, it was burnt on September 16, after the harvest.

2.2. Observations

The CH_4 flux was observed using both the closed- and open-path eddy covariance technique in 2012. Details of the observations can be found in Iwata et al. (2014). Briefly, an ultrasonic anemo-thermometer (DA-600, Kaijo Sonic, Japan), an open-path CH_4 analyzer (LI-7700, Li-Cor, USA) and an open-path infrared CO_2/H_2O gas analyzer (LI-7500, Li-Cor, USA) were installed at a height of 3.35 m above ground to observe the turbulent fluctuations in wind velocities and gas densities. The open-path CH_4 analyzer was installed on March 7. For the closed-path observation, sample air was drawn from the same height as the ultrasonic anemo-thermometer through a 23-m polypropylene tube with an internal diameter of 4 mm, and fed to a closed-path CH_4 analyzer (RMT-200 Fast Methane Analyzer, Los Gatos Research, USA) using an external dry scroll vacuum pump (SH-110, Agilent Technologies, USA). Fluctuations in the water vapor concentration of the sampled air were suppressed using a Nafion dryer (PD-50T-24, Perma Pure, USA). The closed-path observation started on June 11 and ended at the end of September. The open-path CH_4 analyzer was removed on December 11 and CH_4 flux observations ended on that day. All data were recorded at 10 Hz using a datalogger (CR1000, Campbell Scientific, USA).

Mean CH_4 concentrations were also observed at 0.25, 0.52, 0.97, 1.52, and 3.85 m above ground, and CH_4 storage in the atmospheric column below the observation height was determined from this profile data. Sample air was continuously drawn from each height into 0.02-m^3 buffer tanks using pumps (MP-Σ300N, SIBATA, Japan), and air was sent to another closed-path CH_4 analyzer (Fast Greenhouse Gas Analyzer, Los Gatos Research, USA). For the first 10 min in each 30-min interval, the analyzer was used for relaxed eddy accumulation observation. Subsequently, the flowlines were switched among the five levels every minute using electromagnetic valves; i.e., each level was monitored four times for each 30-min interval. Data was scanned at 1 Hz and only the last 10 s of each minute were used to calculate the average. The averaged data were stored in another datalogger (CR1000, Campbell Scientific, USA) and the 30-min average was calculated prior to data analysis.