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Annual variation of methane emissions from forested bogs in West Siberia (2005–2009): a case of high CH_4 and precipitation rate in the summer of 2007

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Abstract

We have been conducting continuous measurements of CH_4 and CO_2 on a network of towers (JR-STATION: Japan-Russia Siberian Tall Tower Inland Observation Network) located in taiga, steppe, and wetland biomes of Siberia. Here we describe measurements from two forested bog sites, Karasevoe (KRS; 58°15′ N, 82°25′ E) and Demyanskoe (DEM; 59°47′ N, 70°52′ E), in West Siberia from 2005 to 2009. Although both CH_4 and CO_2 accumulation (ΔCH_4 and ΔCO_2) during nighttime (duration of 7 h beginning 21:30 LST) at KRS in July 2007 showed an anomalously high concentration, the higher ratios of $\Delta CH_4/\Delta CO_2$ compared with those in other years indicate that a considerably more CH_4 flux occurred relative to the CO_2 flux in response to large precipitation recorded in 2007 (~2.7 mm d^{-1} higher than the climatological 1979–1998 base). Estimated seasonal CH_4 fluxes based on the ratio of $\Delta CH_4/\Delta CO_2$ and the CASA 3-hourly CO_2 flux for the 2005–2009 period exhibited a seasonal variation with a maximum in July at both sites. Annual values of the CH_4 emission from the forested bogs around KRS (approx. 7.8×10^4 km^2) calculated from a process-based ecosystem model, Vegetation Integrative Simulator for Trace gases (VISIT), showed inter-annual variation of 0.54, 0.31, 0.94, 0.44, and 0.41 Tg CH_4 yr^{-1} from 2005 to 2009, respectively, with the highest values in 2007. It was assumed in the model that the area flooded with water is proportional to the cumulative anomaly in monthly precipitation rate.

1 Introduction

Atmospheric CH_4 is the second most important anthropogenic greenhouse gas after CO_2 because of its influence on the Earth's radiation budget by infrared absorption and photochemical reactions in the atmosphere. Its concentration in the troposphere is principally determined by a balance between surface emission and destruction by hydroxyl (OH) radicals. Anthropogenic CH_4 emission sources include fossil fuel combustion, rice agriculture, livestock, landfill and waste treatment, and some biomass

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burning, while major natural sources include wetlands, termites, and the ocean (IPCC, 2007). Long-term trend in the anthropogenic emissions after the industrial revolution in the 1850s produced an exponential increase in global CH_4 content followed by a period of relatively stable concentration from 1999 to 2006 (Dlugokencky et al., 2003; Rigby et al., 2008). The period of stable concentration was partly attributed to a decrease in CH_4 emissions of ~10 Tg from the region north of 50° N (the former Soviet Union) from 1990 to 1995 (Dlugokencky et al., 2003). Inverse calculations have attributed the stabilization of atmospheric CH_4 to a steady decrease in anthropogenic CH_4 emissions between 1990 and 1999 (Bousquet et al., 2006). Bousquet et al. (2006) also showed that anthropogenic CH_4 emissions increased after 1999, but CH_4 concentration in the atmosphere remained relatively constant because of a coincidental decrease in wetland emissions for several years after 1999. Rigby et al. (2008) reported that the CH_4 concentration began to rise again at the beginning of 2007 and speculated that Siberian wetlands were the most likely source because of an anomalously high annual mean temperature over Siberia (~4 °C above the 1961–1990 base climatology). Dlugokencky et al. (2009) examined observational data obtained from the background sites of the National Oceanic and Atmospheric Administration (NOAA) and reported that the increase in atmospheric CH_4 in early 2007 persisted until 2008. They suggested that the very warm temperatures at polar northern latitudes during 2007 likely enhanced the CH_4 emissions from the northern wetlands. Despite the importance of CH_4 emissions from the Siberian wetlands to the globally elevated CH_4 concentration since 2007, substantial uncertainties remain in the estimate of CH_4 flux and responses to climate change. This is due in large part to the sparseness of in situ observation during this period in Siberia. In order to take some steps to rectify the situation, we have been operating an expanding network of towers (JR-STATION: Japan-Russia Siberian Tall Tower Inland Observation Network) located in taiga, steppe, and wetland biomes of Siberia since 2004. Sasakawa et al. (2010) conducted some analysis of the data from the network and found that the number of elevated CH_4 events in the summer was greatest in 2007 when temperature and precipitation rate were the highest in the period

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of 2004–2008 of monitoring over West Siberia. They suggested that the elevated CH_4 events observed in 2007 could be attributed mainly to the enhanced emissions from wetlands.

In this study, we attempt to estimate hourly CH_4 flux from the West Siberian forested bog regions utilizing the observed CH_4 and CO_2 from the JR-STATION monitoring program and semi-climatological CO_2 flux. Five years (2005–2009) of continuous measurements make it possible to characterize seasonal and annual variations of the CH_4 flux. A process-based ecosystem model, Vegetation Integrative Simulator for Trace gases (VISIT), was used to estimate CH_4 emissions from the forested bogs induced by weather conditions.

2 Method

2.1 Site description and measurement system

In this study we focused on two sites from the JR-STATION program; Karasevoe (KRS) tower (58°15′ N, 82°25′ E) on the shore of a 5-km diameter marshy lake and Demyanskoe (DEM) tower (59°47′ N, 70°52′ E) (Fig. 1). Both towers are placed in the middle of the taiga and surrounded by extensive bogs. We installed a freight container equipped with gas analyzers and a data logger at the base of each tower. Atmospheric air was sampled at two levels on the towers; 35 m and 67 m at KRS, and 45 m and 63 m at DEM. Sampled air was dried and then introduced into a non-dispersive infrared analyzer (model LI-820, LI-COR, USA) and a CH_4 semiconductor sensor (Suto and Inoue, 2010). The air-sampling flow path was rotated every 20 min; that is, the high inlet was sampled on the hour at hh:00 LST, the low inlet 20 min later at hh:20 LST, and a reference gas 40 min later at hh:40 LST (i.e., 20 min after the low inlet sampling). For each 20-min sampling period, air was pumped continuously through the sample line, stainless tube containing chemical desiccant, NDIR cell, and CH_4 sensor for 17 min; for the following 3 min, the data produced by the sensors were averaged and taken as

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the representative data for the applicable 1 h period. Thus both data from high and low inlets were shown as the data at hh:30 LST. The more detail information of the system is described in Sasakawa et al. (2010).

2.2 Three-hourly CO_2 flux

We calculated daily CH_4 flux with measured CH_4 concentration, CO_2concentration, and semi-climatological CO_2 flux from a model. Three-hourly terrestrial biosphere CO_2 fluxes were generated from the monthly Net Ecosystem Production (NEP) flux of the Carnegie–Ames–Stanford Approach (CASA) ecosystem model (Randerson et al., 1997) using a procedure similar to that of Olsen and Randerson (2004). The variability was generated using 2-m temperature and surface short-wave radiation data from the JMA Climate Data Assimilation System (JCDAS; Onogi et al., 2007) on a $1^\circ \times 1^\circ$ grid. The respiration was then rescaled to maintain the same monthly average flux as the original NEP. This biospheric flux has zero annual mean flux everywhere (i.e., a neutral biosphere flux).

2.3 Ecosystem model

Monthly CH_4 fluxes of wetlands were simulated with a process-based ecosystem model, VISIT (Inatomi et al., 2010; Ito, 2010), to evaluate the variation of fluxes responding to weather and biological conditions. VISIT consists of carbon, nitrogen, and water cycle components, each of which is composed of several functional compartments such as leaves, stems, roots, dead biomass, and organic soil. In the model, wetland CH_4 efflux is estimated using a semi-mechanistic scheme (Walter and Heimann, 2000), in which wetland soils are stratified into 20 layers of 5 cm thickness each. Wetland distribution is determined on a $0.5^\circ \times 0.5^\circ$ grid based on Global Lakes and Wetland Database (GLWD, Lehner and Döll, 2004) (Fig. 1). To include the spatial heterogeneity of wetlands, CH_4 fluxes are separately estimated for flooded (i.e., inundation) and non-flooded (i.e., drainage) fractions, each of which has different water-table depths.

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Average inundation fraction during the growing period (May–August) is derived from the SSM/I observation for 1993–2000 (e.g., Prigent et al., 2007); unrealistic monthly fluctuation in the inundation fraction is avoided by assuming a base line inundation fraction during the growing period. Average water-table depths of the inundation and drainage surfaces of wetland are assumed as 0 and −25 cm respectively. Inter-annual variability in the water-table depth of the inundation and drainage areas is estimated from cumulative precipitation anomaly from 2001–2009 mean based on the reanalysis data from the US National Centers for Environmental Prediction (NCEP/NCAR; Kalnay et al., 1996) and overlaid at each grid. To assess the possible range of estimation, a high (+1 mm water table depth/+1 mm precipitation anomaly) and a low (similarly, +0.2 mm/+1 mm) response cases are conventionally examined. At layers lower than the water table, CH_4 production is estimated as a function of temperature and plant carbon supply, which is obtained from the vegetation production scheme of the model. Three pathways of CH_4 emission from the soil surface are included in the model: physical diffusion, plant-mediated transport, and ebullition.

3 Results and discussions

3.1 Summer diurnal variation in CO_2 and CH_4 concentration

Both CO_2 and CH_4 at KRS and DEM showed clear diurnal variation during the summer (Fig. 2). As far as CO_2 is concerned, its diurnal cycle is basically controlled by plant photosynthesis during the daytime and respiration during the nighttime. The lower atmosphere nighttime CO_2 concentration is amplified by the development of stable nocturnal boundary layer (NBL). For CH_4, whose emission from wetlands is relatively steady during the day in the summer, the development of NBL and the lowering of the mixed layer (ML) height is the major factor contributing to the nighttime buildup of its concentration, and thus causing the observed diurnal variation. ML in the lower atmosphere over Siberia is seasonally pronounced, varying from 200–600 m in the winter

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to as much as 2800 m in the summer (Lloyd et al., 2002). Diurnally, the ML begins to develop in the morning and the ML height continues to rise during the daytime. This causes a decrease in the CH_4 concentration due to increased volume of dilution and the mixing with the free tropospheric air with lower CH_4 concentration. After sunset, the convective ML collapses, followed by CH_4 accumulation. The timing of the diurnal maximum in CO_2 (04:30–6:30 LST) was observed to occur earlier than that in CH_4 (05:30–8:30 LST) (Fig. 2). This slight lag in the peaking of the concentration of CO_2 and CH_4 was caused mainly by the fact that photosynthesis due to solar radiation started before the development of convective ML.

Figure 2 does not indicate any clear increase in the nighttime CO_2 concentration while the daytime CO_2 concentration from 2005 to 2009 shows a general increase. This is because the degree of nocturnal accumulation strongly depends on the local daily regional surface flux and weather condition (atmospheric stability) while daytime concentrations represent values from wider region due to well mixed condition of the atmosphere. Daytime and nighttime CH_4 concentrations did not show any discernable increasing trend, but did exhibit positive anomaly in July 2007 both at KRS and DEM.

3.2 Methane flux calculation using nocturnal CO_2 and CH_4 accumulation

Three-hourly CASA CO_2 flux averaged over a rectangular area ($\pm 3^\circ$ latitude, $\pm 1^\circ$ longitude) around the towers (KRS and DEM) showed clear diurnal variation with negative and positive values during the daytime and the nighttime, respectively, in the summer (not shown). Consecutive three nocturnal fluxes of CO_2 between 20:00 LST (day x) and 05:00 LST (day x+1) due to respiration showed little variation from day to day regardless of month or year. Here we define gas accumulation (ΔCO_2 and ΔCH_4) as the measured concentration difference between the concentration at 21:30 LST and the accumulated concentration at early next morning (04:30 LST). ΔCO_2 and ΔCH_4 concentration values reflect influences of atmospheric stability (ML depth) and the magnitude of the flux. In order to eliminate the influence of the atmospheric stability, we used the daily ratio of $\Delta CH_4/\Delta CO_2$ that indicates only the relative strength of the flux of CH_4

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and CO_2. Scatter plots of ΔCH_4 vs. ΔCO_2 how that the CH_4 flux was generally greater than 1 per 400 CO_2 flux (Fig. 3). It is also noted in Fig. 3 that the ratios of $\Delta CH_4/\Delta CO_2$ in July 2007 at KRS show a general increase in the CH_4 flux of more than 4 times compared to the CO_2 flux (ratio values $\geqq$ 4/400 = 1/100). This corresponds to the particularly hot and wet weather in West Siberia during the summer of 2007, likely creating favorable conditions for increased CH_4 emissions from bogs. Remarkable high ratios were also seen in August 2009 at KRS.

In order to estimate the actual daily CH_4 flux from CASA 3-hourly CO_2 flux normalized with the observed CH_4 and CO_2 accumulation on a certain day (day x), we used the average of three midnight data between 20:00 LST (day x) and 05:00 LST (day x+1) as CO_2 flux (F_{CO_2}). Daily CH_4 flux was then calculated with the following Equation:

$$F_{CH_4} = F_{CO_2} \times \Delta CH_4/\Delta CO_2. \quad (1)$$

The CH_4 flux calculated from this Equation reflects averaged emissions from the surface inside the targeted rectangular area around each tower. Calculated CH_4 flux displays a clear seasonal cycle with maximum in July (Fig. 4), corresponding to the clear rise of daytime CH_4 concentrations reported by Sasakawa et al. (2010). Methane fluxes in July 2007 around KRS were noticeably higher than those in other years (Fig. 4a). The longest upper quartile range for July 2005 resulted from (1) very few data obtained in the month and (2) one anomalous datum for the month which is plotted significantly above the 100:1 ratio line in Fig. 3. In the years following 2007, CH_4 fluxes in July exhibited higher values than those in the previous years. Generally CH_4 fluxes around DEM were lower than those around KRS and no anomalous high flux in July 2007 appeared (Fig. 4b). The calculated CH_4 fluxes in July around KRS were much higher than the regional mean flux estimates for the wetlands (bogs, swamps, and tundra) published by the NASA Goddard Institute for Space Studies (GISS) (Fung et al., 1991). The difference in flux values is possibly due to the relatively coarse resolution of the GISS flux map which did not resolve the many small ponds and lakes that are distributed throughout the taiga and extensive bogs surrounding the KRS tower; these small water bodies

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can act as a significant source of CH_4 particularly during July, the hottest part of the summer. On the other hand, the GISS data show higher flux estimates around DEM compared to our calculated values (Fig. 4b), perhaps pointing to an overestimation of CH_4 flux by GISS for wetlands, at least in regions around DEM.

In situ measurements of CH_4 flux from Siberian wetlands are scarce and limited to short periods. Panikov and Dedysh (2000) reported that monthly average CH_4 fluxes measured using a static chamber technique at west Siberian bog near the village of Plotnikovo (56°51′ N, 82°58′ E) in July and/or August 1993–1997 ranged from 137 to 465 mg m^{-2} day^{-1} (5.7–19.4 mg m^{-2} h^{-1}). Friborg et al. (2003) measured CH_4 flux with eddy correlation technique at the same bog in West Siberia during the summer of 1999; the average CH_4 flux in three campaigns varied from 75 to 222 mg m^{-2} day^{-1} (3.1–9.3 mg m^{-2} h^{-1}). Whereas these in situ measurements displayed emission rates specific to certain spots, Takeuchi et al. (2003) extrapolated field observations taken in July 1993 and 1994 to an area 400×400 km^2 adjacent to Plotnikovo, using land cover classifications derived from NOAA AVHRR and SPOT HRV images, which should be comparable with our calculated regional CH_4 fluxes in this study. Their estimation of regional average CH_4 flux for July 1993 and 1994 was 59.3 mg m^{-2} day^{-1} (2.5 mg m^{-2} h^{-1}), which falls in the interquartile range for July around the DEM and KRS region, except for July 2007.

3.3 Estimation of CH_4 emissions from wetlands with VISIT model

Based on model simulations, Bohn et al. (2007) evaluated the sensitivity of CH_4 emission from a 100×100 km^2 region near Plotnikovo to increases in temperature and precipitation. They found that higher temperatures alone did not always increase CH_4 emissions from wetlands but higher precipitation alone raised water tables and expanded the saturated area, resulting in a net increase in CH_4 emissions. The precipitation rate in the latitudinal zone of 55–65° N between 65° E and 85° E exhibited anomalously high values in the summer of 2007 (Sasakawa et al., 2010), which could

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explain the anomalously high CH_4 flux estimated for the KRS region in July 2007. Monthly mean precipitation rate for the area around the KRS region obtained from Global Precipitation Climatology Project (GPCP) version 2.1 combined precipitation data set (Adler et al., 2003) showed high precipitation rates of 4.4 and 3.6 mm d^{-1} in May and June 2007, respectively. These values are 2.7 and 1.6 mm d^{-1} higher than the respective monthly averages for the 1979–1998 climatological period, and represent the highest values during the period of our study. These precipitation rates of about two times the climatological mean (Supplementary Fig. 1) probably elevated the water table in the KRS region, leading to an increase in CH_4 emissions from wetlands. In June and July 2009, the anomalies were also high (1.3 and 1.0 mm d^{-1} above the climatology) in the KRS region, likely leading to an elevated CH_4 flux in August (Fig. 4a).

In order to confirm these speculations, we simulated CH_4 emissions from wetlands with VISIT model, in which the dimension of the flooded area was assumed to expand proportionally to the monthly precipitation anomaly rates (see Sect. 2.3). The regional mean rates of the simulated CH_4 emission generally reproduced the observed seasonal variation at KRS and DEM, with maximum in July (Fig. 4). The overall regional strength of the CH_4 emission at KRS agreed well with the results of the observation-based calculation with Eq. (1) despite the overestimation at DEM. Extremely high regional CH_4 emission in July 2007 at KRS was also reproduced as 3.5 and 6.6 mg CH_4 m^{-2} h^{-1} in low and high response cases, respectively. These results strongly support the hypothesis that the high precipitation rate in the summer of 2007 accounts for high CH_4 emissions from regions around KRS.

4 Conclusions

This paper presented summer diurnal variation in CH_4 and CO_2 concentrations observed from 2005 to 2009 at two forested bog sites in West Siberia (KRS and DEM) as part of the JR-STATION program. Both greenhouse gases accumulated in the lower atmosphere during the nighttime due to stable boundary layer and flux from the ground.

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Utilizing the nighttime accumulations of both greenhouse gases (ΔCH_4 and ΔCO_2), we found that the ratio of ΔCH_4 to ΔCO_2 indicated daily CH_4 flux magnitude generally greater than 1 per 400 CO_2 flux. Using the 3-hourly terrestrial biosphere CO_2 fluxes calculated from monthly NEP flux generated by the CASA ecosystem model, as well as the measured $\Delta CH_4/\Delta CO_2$ ratio, we obtained daily CH_4 fluxes. The calculated seasonal variation showed a maximum in July at both KRS and DEM, but anomalously high values in 2007 only at KRS. Using VISIT, an ecosystem model in which the dimension of the flooded area is assumed to expand proportionally with the cumulative anomaly in monthly precipitation rate, we confirmed that the anomalously high CH_4 flux in the summer of 2007 around KRS resulted from high precipitation rate. Integrated CH_4 emissions in a high (low) response case from the forested bogs around KRS (approx. 7.8×10^4 km^2) resulted in 0.54 (0.39), 0.31 (0.34), 0.94 (0.48), 0.44 (0.36), and 0.41 (0.39) Tg CH_4 yr^{-1} for years 2005 to 2009, respectively. Although the anomalous CH_4 emissions from the targeted area around KRS by itself does not explain all the recently observed variability in the global CH_4 concentration growth, extrapolation of the result to rest of the Siberian wetlands (approximately 17 times that of the targeted area around KRS which is about 1.32×10^6 km^2 (Sohngen et al., 2005)) would indicate a significant role Siberia plays in influencing global atmospheric CH_4 variation.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/10/27759/2010/acpd-10-27759-2010-supplement.pdf.

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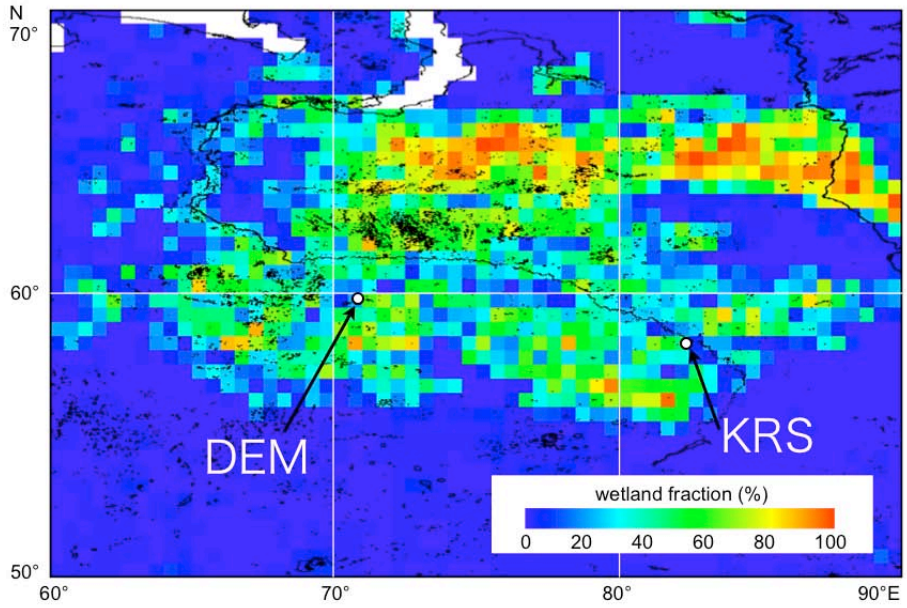

Fig. 1. Wetland distribution map based on GLWD (Lehner and Döll, 2004) used in VISIT model. Grid color indicates the wetland fraction for each grid. For example, 50% (green) means that half of the surface in the grid is regarded as wetland.

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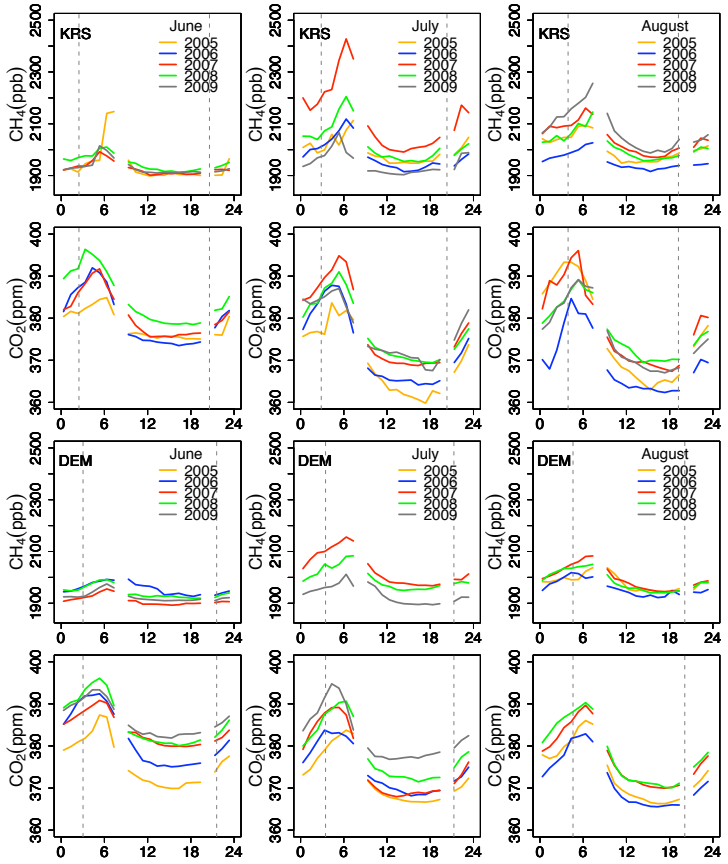

Fig. 2. Mean diurnal variation of CO_2 and CH_4 concentrations during summer (June, July, and August) at KRS and DEM. The data from high inlet were annually averaged. Vertical dotted lines indicate the mean time of sunrise and sunset. Every 12 h all three measurements for the hour were of standard gases; thus there are no data at 08:30 LST and 20:30 LST.

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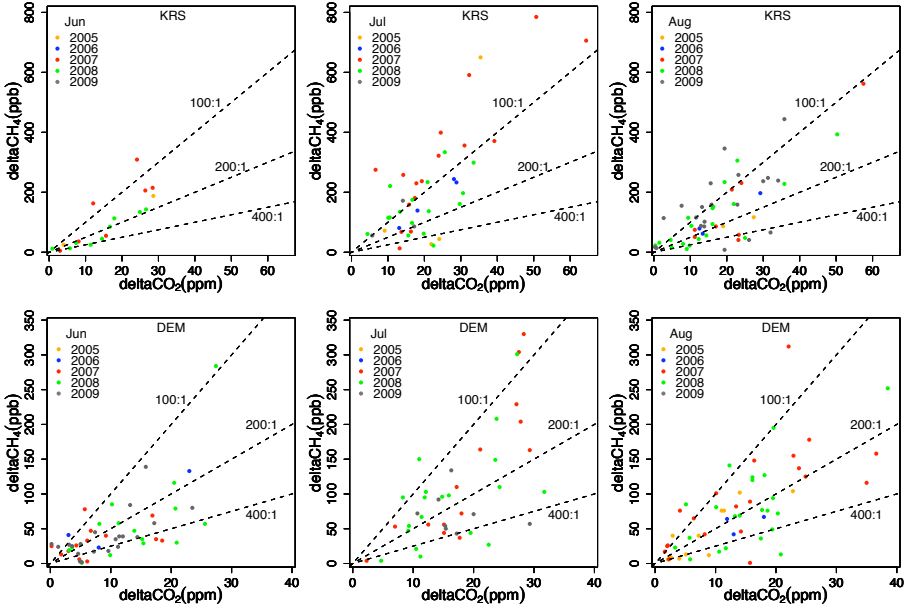

Fig. 3. Relationship between ΔCO_2 and ΔCH_4 during summer at KRS (upper panels) and DEM (lower panels). ΔCO_2 and ΔCH_4 are defined as the measured concentration difference between the concentration at 21:30 LST and the accumulated concentration in the early morning the next day at 04:30 LST. Dotted lines indicate expected relationship from environment in CO_2-flux:CH_4-flux = 100:1, 200:1, and 400:1.

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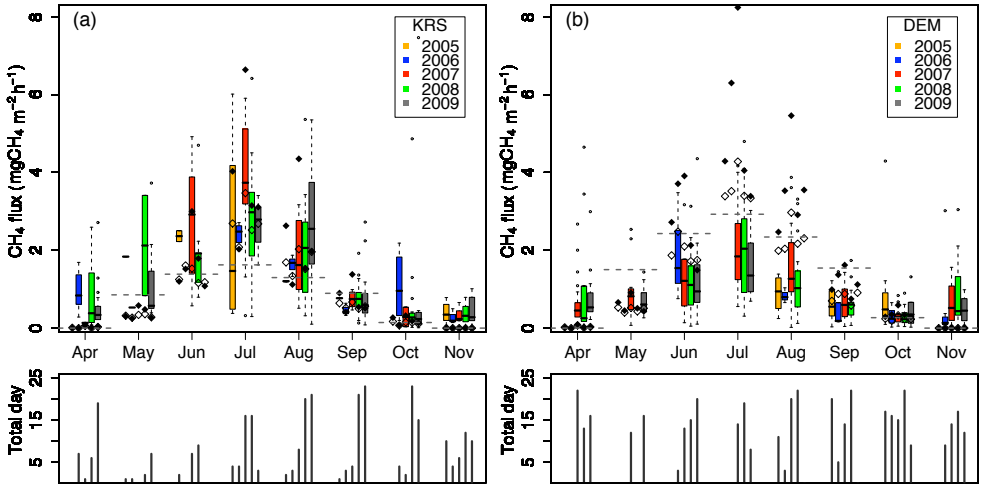

Fig. 4. Box-and-whisker diagrams of daily CH_4 flux calculated with nocturnal CO_2 and CH_4 accumulation over an area ($\pm 3^{\circ}$ latitude, $\pm 1^{\circ}$ longitude) around **(a)** KRS and **(b)** DEM. The diagrams are defined as follows: the median is the thick line in the box; the bottom and top of the box are the lower and upper quartiles, respectively; the whiskers extend to the most extreme data point which is no more than 1 time the interquartile range from the box; individual outliers are shown as open circles outside the whiskers. Horizontal dotted lines indicate regional means of fluxes from the GISS wetlands (bogs, swamps, and tundra) around the towers. Closed (open) diamonds denote monthly CH_4 flux of high (low) response case simulated with VISIT model. The bottom figures show the number of calculated day for each month and year. It depends mostly on the number of the obtained data. No winter data are shown since there is almost no diurnal variation during winter (Sasakawa et al., 2010).

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