Annual variation of CH$_4$ emissions from the middle taiga in West Siberian Lowland (2005–2009): a case of high CH$_4$ flux and precipitation rate in the summer of 2007

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(Manuscript received 7 October 2011; in final form 13 January 2012)

ABSTRACT

We described continuous measurements of CH$_4$ and CO$_2$ concentration obtained at two sites placed in the middle taiga, Karasevoe (KRS) and Demyanskoe (DEM), in West Siberian Lowland (WSL) from 2005 to 2009. Although both CH$_4$ and CO$_2$ accumulation ($\Delta$CH$_4$ and $\Delta$CO$_2$) during night-time at KRS in June and July 2007 showed an anomalously high concentration, higher ratios of $\Delta$CH$_4$/$\Delta$CO$_2$ compared with those in other years indicated that a considerably higher CH$_4$ flux occurred relative to the CO$_2$ flux. The daily CH$_4$ flux calculated with the ratio of $\Delta$CH$_4$/$\Delta$CO$_2$ and terrestrial biosphere CO$_2$ flux from an ecosystem model showed a maximum in July at the both sites. Although anomalously high flux was observed in June and July 2007 at KRS, only a small flux variation was observed at DEM. The high regional CH$_4$ flux in June and July 2007 at KRS was reproduced using a process-based ecosystem model, Vegetation Integrative Simulator for Trace gases (VISIT), in response to high water table depth caused by the anomalously high precipitation during the summer of 2007.

Keywords: methane, Siberia, taiga, West Siberian Lowland, tower observation

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 through infrared absorption and its role in the photochemistry of 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, waste treatment and biomass burning, while major natural sources include wetlands, termites and the ocean (IPCC, 2007). The anthropogenic emissions following the industrial revolution in the 1850s produced an exponential increase in the 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 has been 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). This is consistent with the results of inverse calculations, which have attributed the stabilisation 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 the 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 increase 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 the observational data obtained from the background sites operated by the National Oceanic and Atmospheric Administration (NOAA) and reported that the increase in the atmospheric CH$_4$ concentration in the 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 estimating the CH$_4$ fluxes and responses to climate change. This is mainly due to the sparseness of in situ observation during this period (~2007) in Siberia. For example, Kozlova et al. (2008) presented the first results of continuous in situ CH$_4$ concentration measured at the Zotino Tall Tower Observatory (ZOTTO; 60°48′N, 89°21′E) in the boreal forest of central Siberia, but the study showed measurements only from November to December, 2006. Recently, a 1-year time series of CH$_4$ concentration (May 2009–April 2010) at ZOTTO was published by Winderlich et al. (2010). The CH$_4$ concentration had no seasonal variation but showed a distinct diurnal cycle during the summer (July 2009). In order to increase the spatio-temporal coverage, we have been operating, since 2004, an expanded network of towers (JR-STATION: Japan-Russia Siberian Tall Tower Inland Observation Network) located in taiga, steppe and wetland biomes of Siberia. Sasakawa et al. (2010) conducted some analysis of the data from the network and found that the number of elevated CH$_4$ concentration events in the summer was greatest in 2007 when temperature and precipitation rates were highest for 2004–2008 monitoring period over West Siberia. They suggested that the elevated CH$_4$ concentration events observed in 2007 could be attributed mainly to the enhanced emissions from wetlands.

In this study, we estimated hourly CH$_4$ flux from the middle taiga in WSL utilising the observed CH$_4$ and CO$_2$ concentration from the JR-STATION monitoring program and CO$_2$ flux from an ecosystem model. Five years (2005–2009) of continuous measurements have made it possible to characterise the seasonal and annual variations of the CH$_4$ flux. A process-based ecosystem model, Vegetation Integrative Simulator for Trace gases (VISIT) (Inatomi et al., 2010; Ito, 2010), was used to estimate the CH$_4$ fluxes responding to weather and biological 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) and Demyanskoe (DEM) tower (59°47′N, 70°52′E) (Fig. 1). Both towers are placed in the middle taiga and surrounded by bogs. No large city exists in 200 km around both towers; thus, CH$_4$ emitted from wetlands is the major contributor to CH$_4$ variation particularly during summer (Sasakawa et al., 2010). We installed a freight container equipped with gas analysers 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 analyser (model LI-820, LI-COR, USA) and an originally developed CH₄ 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, the low inlet 20 min later at hh:20, and a reference gas 40 min later at hh:40 (i.e. 20 min after the low inlet sampling). For each 20-min sampling period, air was pumped continuously through the sample line, a stainless tube containing chemical desiccant (magnesium perchlorate), NDIR cell and CH₄ sensor for the first 17 min (flushing); for the following 3 min, the data produced by the sensors were averaged and taken as the representative data for the applicable 1-h period. Thus, both the data from the high and low inlets were shown as the data at hh:30. Measurement precision was ±0.3 ppm and ±3 ppb for CO₂ and CH₄, respectively (Sasakawa et al., 2010).

### 2.2. Methane flux estimation

The degree of nocturnal accumulation in CO₂ and CH₄ concentrations generally depends on the regional surface fluxes and atmospheric stability. We then estimated the daily CH₄ flux \( F_{\text{CH}_4} \) from terrestrial biosphere CO₂ flux \( F_{\text{CO}_2} \) normalised with the observed CH₄ and CO₂ accumulation on a certain day:

\[
F_{\text{CH}_4} = F_{\text{CO}_2} \times \frac{\Delta \text{CH}_4}{\Delta \text{CO}_2}. \tag{1}
\]

Here, we defined gas accumulation \( \Delta \text{CO}_2 \) and \( \Delta \text{CH}_4 \) as the measured concentration difference between the concentration at 21:30 Local Standard Time (LST) and the elevated concentration at early next morning (4:30 LST). The ratio of \( \Delta \text{CH}_4/\Delta \text{CO}_2 \) indicated only the relative strength of the flux of CH₄ and CO₂. The CH₄ flux calculated from eq. (1) reflected averaged emissions around each tower. For \( F_{\text{CO}_2} \), three-hourly CO₂ fluxes were generated from the monthly Net Ecosystem Production (NEP) fluxes produced by the Carnegie-Ames-Stanford Approach (CASA) ecosystem model (Randerson et al., 1997) on a 1° × 1° grid using a procedure similar to that of Olsen and Randerson (2004). We used the data from the JMA Climate Data Assimilation System (JCDAS; Onogi et al., 2007) as the source of meteorological fields. First, the three-hourly downward short-wave radiation was calculated by fitting the six-hourly JCDAS data to a theoretical clear-sky solar radiation function. Then, the three-hourly Gross Primary Production (GPP) within each month was estimated by distributing the monthly GPP [Net Primary Production (NPP) × 2] in accordance with the radiation data. Thereafter, the monthly respiration \( R_e \) was distributed within each month according to:

\[
R_e(t) = R_{e,0} \times Q_{10}^{(T(t) - T_{10})/10}
\]

where \( Q_{10} \) was set at 1.5 (Olsen and Randerson, 2004) and \( T \) was obtained from the 2-m JCDAS temperature. Then, \( R_{e,0} \) was adjusted so that the monthly NEP (GPP - \( R_e \)) approached the same values as the original CASA NEP data, with zero mean annual biospheric flux at every grid point. The three-hourly CASA CO₂ fluxes showed clear diurnal variation with negative and positive values during the daytime and the night-time, respectively, in the summer (not shown). We used the average of three midnight data [21:30 LST (day \( x \)), 0:30 LST (day \( x+1 \)) and 3:30 (day \( x+1 \)) over the targeted area \( (±3° \text{ latitude}, ±1° \text{ longitude}) \) around the towers (KRS and DEM) as \( F_{\text{CO}_2} \).

Although most of the results from the low inlet indicated the same as those from the high inlet, we showed those from the high inlet to remove occasional local influence. It should be noted that the calculated CH₄ flux turned out to be the minimum estimated value because some wetlands showed higher CH₄ flux during the daytime than during the night-time (e.g. Hargreaves and Fowler, 1998; Long et al., 2010). However, the elevated CH₄ flux during the nighttime was not always observed (Long et al., 2010), and it has been shown that, at some wetlands, a diurnal cycle of CH₄ flux is not observed (Werner et al., 2003; Rinne et al., 2007).

### 2.3. Ecosystem model

Monthly CH₄ fluxes from wetlands were estimated using the VISIT model (Inatomi et al., 2010; Ito, 2010) to evaluate the variation of gas fluxes responding to weather and biological conditions. Figure 2 shows a schematic diagram of the CH₄ exchange processes employed in VISIT. The model consists of carbon, nitrogen and water cycle subschemes, each of which is composed of several functional compartments such as leaves, stems, roots, dead biomass and organic soil. Plant photosynthetic CO₂ uptake, allocation, biomass growth and mortality are simulated in the carbon cycle as part of an ecophysiological process (Ito and Oikawa, 2002). Wetland CH₄ flux is simulated using a semi-mechanistic scheme (Walter and Heimann, 2000), in which three processes of CH₄ flux emission are considered: physical diffusion, plant-mediated transportation and ebullition. The physical diffusion rate depends on the CH₄ concentration gradient between the surface and soil air, which is affected by the CH₄ production and oxidation within the soil. In the soil, the CH₄ production rate is determined by microbial activity and substrate supply from plants, producing sensitivity to temperature variability that leads clearly to seasonal cycle in.
Spatial heterogeneity in diffusivity through soil pore spaces is determined on the basis of sand/clay composition data (Hall et al., 2006) and watertable depth. The plant-mediated transport of CH₄ is dependent on the plant growing stage determined by the cumulative temperature and biome-specific rooting depth (typically, 20 cm for wetlands). The ebullition flux occurs only when the CH₄ concentration exceeds 500 mol L⁻¹ (Walter and Heimann, 2000). It should be noted that, due to the lack of site-specific ecological measurements, several variables in the model are assigned typical values reflecting the general characteristics of the northern wetlands. This introduced a potential uncertainty in our study, which will be discussed later.

Wetland distribution is determined on a 0.5° × 0.5° grid based on Global Lakes and Wetlands Database (GLWD, Lehner and Döll, 2004) (Fig. 1). A distribution of natural vegetation type including both uplands and wetlands is derived from the global data-set (Olson et al., 1983; Ramankutty and Foley, 1999). For performing broad-scale simulations, wetland soils are stratified into 20 layers of 5 cm thickness each. To include the spatial heterogeneity of wetlands, CH₄ fluxes are separately estimated for flooded (i.e. inundation) and non-flooded fractions of the ground surface, each of which has different water table depths.

Thus, the total CH₄ emission (E) for each grid cell is obtained as:

$$E = w \times (f_{\text{inund}} \times E_{\text{inund}} + f_{\text{drain}} \times E_{\text{drain}})$$  (3)

where w represents the wetland fraction in each grid cell, and f and E denote the land fraction and CH₄ exchange flux of inundation and drainage parts (subscripts), respectively. Monthly averaged inundation fraction (f_inund) is derived from a passive microwave Special Sensor Microwave/Imager (SSM/I) observation for 1993–2000 (e.g. Prigent et al., 2007). Because we estimated the inundation fraction on the basis of seasonal variation for each grid cell in this study, snow cover and extensive flooding after snow melting could in some cases affect the baseline. To avoid these apparent variations (e.g. too much severe drying after a spring flood) during the growing period (May–August), we decided to use the averaged inundation fraction derived from the SSM/I observation during the period. The baseline water table depths of the inundated and drained wetland surfaces were assumed to be 0 and ~25 cm, respectively, based on a simulation at West Siberian wetlands (Bohn et al., 2007). At layers lower than the water table, the CH₄ production is estimated in the model as a function of temperature and plant carbon supply that is obtained from the vegetation production scheme. The simulated
CH$_4$ flux reflected the minimum estimated value in our study since the assumed watertable depth for a drained surface (~25 cm) was the lowest case scenario; higher water table depths could produce higher CH$_4$ fluxes due to the resulting reduction in the oxidation zone (Fig. 2).

We also evaluated the influence of precipitation rate on the CH$_4$ emission from wetlands. Inter-annual variability in the water table depth was estimated from the cumulative precipitation anomaly at each model grid as deviation from the 2001 to 2009 mean, which was obtained from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). 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 were examined.

3. Results and discussions

3.1. Summer diurnal variation in CO$_2$ and CH$_4$ concentration

Both the CO$_2$ and CH$_4$ concentration at KRS and DEM showed clear diurnal variation during the summer (Fig. 3).

![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 8:30 LST and 20:30 LST.](image-url)
Diurnal amplitude exhibited maximum in July for both CO$_2$ (>15 ppm) and CH$_4$ (>100 ppb). If the wind blows from different specific directions between day and night (e.g., a northerly in the daytime and a southerly in the nighttime), the observed diurnal variation could be caused by the footprint. However, there was no dominant wind direction and no particular difference in the wind direction between day and night, allowing for an assumption of relatively homogeneously distributed sources of CO$_2$ and CH$_4$ over the tower footprint; that is, sources of these gases were essentially co-located. The diurnal cycle of CO$_2$ is basically controlled by plant photosynthesis and respiration during the daytime and respiration during the nighttime. The lower atmosphere night-time CO$_2$ accumulation is amplified by the development of a stable nocturnal boundary layer (NBL). For CH$_4$, the emission from wetlands is amplified by the development of a stable nocturnal boundary layer over the tower footprint; that is, sources of these gases in the peaking of the concentration of CO$_2$ and CH$_4$ concentration (5:30 LST) was observed to occur earlier than that in CH$_4$ concentration. After sunset, the convective ML collapses, followed by CH$_4$ accumulation. In our study, the daytime and night-time CH$_4$ while the daytime concentrations generally represent values with face flux and weather condition (atmospheric stability), accumulation strongly depends on the daily regional surface flux and weather condition (atmospheric stability), while the daytime concentrations generally represent values from a wider region due to the well-mixed condition of the atmosphere. In our study, the daytime and night-time CH$_4$ concentrations did not show any discernible increasing trend, but did exhibit positive anomaly in July 2007 both at KRS and DEM.

3.2. Estimation of CH$_4$ emissions

Scatter plots of $\Delta$CH$_4$ versus $\Delta$CO$_2$ at our sites show that the CH$_4$ flux was generally greater than 1/400 CO$_2$ flux (Fig. 4). It is also noted in Fig. 4 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 four times compared to the CO$_2$ flux (ratio values $\geq$ 4/400 = 1/100). This corresponded to the particularly hot and wet weather in West Siberia during the summer of 2007, likely creating favourable conditions for increased CH$_4$ emissions from bogs. Remarkable high ratios were also seen in August 2009 at KRS when the precipitation rate was anomalously high during summer (see Section 3.3). No obvious seasonality was found in the ratio of $\Delta$CH$_4$/ $\Delta$CO$_2$, although summer maximum was observed in July at KRS.

Calculated CH$_4$ flux with eq. (1) displayed a clear seasonal cycle, with maximum in July (Fig. 5), corresponding to the clear increase in daytime CH$_4$ concentrations as reported by Sasakawa et al. (2010). There was also considerable monthly variability in CH$_4$ flux, particularly during summer. The seasonality was produced mainly because the nocturnal CASA CO$_2$ fluxes due to respiration showed a maximum in June and July ($\sim$ 6 μmol m$^{-2}$ s$^{-1}$) and a minimum in winter ($< 1$ μmol m$^{-2}$ s$^{-1}$).

Methane fluxes in June and July 2007 around KRS were noticeably higher than those in other years (Fig. 5a). The longest upper quartile range for July 2005 resulted from (1) very few data obtained during the month and (2) one anomalous datum for the month, which is plotted significantly above the 100:1 ratio line in Fig. 4. Methane fluxes in August 2009 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. 5b). It should be noted that the anomaly in CH$_4$ flux was quite different between the two sites, although both sites were placed in the middle taiga in WSL. The calculated CH$_4$ fluxes in June, July and August around KRS were higher than the regional mean flux estimates for the wetlands from Goddard Institute for Space Studies (GISS) (Fung et al., 1991; Patra et al., 2009) (Fig. 5a). The GISS data-set applied scaling factors to each individual component as shown in Patra et al. (2009); this flux varies from month to month, but does not change from year to year for the same month. The difference in flux values was possibly due to the relatively coarse resolution of the GISS flux map, which does not resolve many of the small ponds and lakes that are distributed throughout the taiga and extensive bogs surrounding the KRS tower; these small water bodies can act as a significant source of CH$_4$, particularly during summer (e.g., Repo et al., 2007). Repo et al. (2007) reported that the daily mean emission of CH$_4$ from small wetland lakes in...
western Siberia ranged from 1.1 to 120 mg m\(^{-2}\) d\(^{-1}\), which can contribute to the difference. On the other hand, the GISS data showed higher flux estimates around DEM compared to our calculated values (Fig. 5b), perhaps pointing to an overestimation of CH\(_4\) flux by GISS for wetlands, at least in the regions around DEM.

In situ measurements of CH\(_4\) flux from Siberian wetlands are scarce and limited to short periods. Panikov and Dedovsh (2000) reported that the monthly average CH\(_4\) fluxes measured using a static chamber technique at a 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\(^{-2}\) d\(^{-1}\). 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\(^{-2}\) d\(^{-1}\). Whereas these in situ measurements displayed emission rates specific to a narrow region, Takeuchi et al. (2003) extrapolated field observations taken in July 1993 and 1994 to an area 400 km \(\times\) 400 km adjacent to Plotnikovo, using land cover classifications derived from NOAA AVHRR and SPOT HRV images; these results were 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\(^{-2}\) d\(^{-1}\), which fell in the interquartile range for July around the DEM and KRS region, except for July 2007.

3.3. **Estimation of CH\(_4\) with VISIT model**

We simulated CH\(_4\) emissions from the middle taiga with the VISIT model. The regional mean rates of the simulated CH\(_4\) emission generally reproduced the observed seasonal variations at KRS and DEM, with maximum in July (Fig. 5). 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. However, annual variation was small and anomalously high CH\(_4\) emission in June and July 2007 at KRS was not reproduced. This might be because observational information on factors (water table, rooting depth, etc.) influencing the calculation of CH\(_4\) emission from forested bogs is quite limited.

Based on model simulations, Bohn et al. (2007) evaluated the sensitivity of CH\(_4\) emission from a 100 km \(\times\) 100 km 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 the CH\(_4\) emissions. Monthly mean precipitation rate for the area around the KRS region obtained from the 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 were 2.7 and
1.6 mm d$^{-1}$ higher than the respective monthly averages for the 1979–1998 climatological period and represented the highest values during the period of our study. These precipitation rates of about two times the climatological mean (Fig. 6) probably elevated the water table in the KRS region, leading to an increase in the CH$_4$ emissions from the surrounding wetlands. In June and July 2009, the precipitation anomalies were also high (1.3 and 1.0 mm d$^{-1}$ above the climatology) in the KRS region and most likely resulted in an elevated CH$_4$ flux in August (Fig. 5a). The slight time lag between the time of high precipitation rate and the time of increased CH$_4$ emission was likely due to the poor drainage in the West Siberian wetlands (relatively flat terrain) and low evapotranspiration rate.

In order to verify the model sensitivity of CH$_4$ flux to water table depth, we modified the VISIT model so that the dimension of the water table depth was assumed to expand proportionally to the monthly precipitation anomaly rates (see Section 2.3). As shown in Fig. 2, the elevated water table depth increases the CH$_4$ production zone and decreases its oxidation zone in the model, leading to an increase in the CH$_4$ flux from the wetlands. The simulated regional mean CH$_4$ emission rates showed a maximum in July. The extremely high regional CH$_4$ emission in June and July 2007 at KRS was reproduced as 72 (37) and 159 (83) mg CH$_4$ m$^{-2}$ d$^{-1}$ in the high (low) response case (Fig. 5a), in response to high water table depth caused by the anomalously high precipitation during the summer of that year. These results support the hypothesis that the high precipitation rate in the summer of 2007 accounted for the high CH$_4$ emissions from regions around KRS.

Integrated CH$_4$ emissions in a high (low) response case from the middle taiga around KRS ($\pm^3\$ latitude, $\pm^1\$ longitude; approximately $7.8 \times 10^4$ 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 the years 2005–2009, respectively. Most of the previous studies (e.g. Rigby et al., 2008; Dlugokencky et al., 2009) speculated that the Siberian wetlands were the main source for the CH$_4$ increase from the beginning of 2007. Although the emission in 2007 around KRS was two to three times greater than those in other years, the anomalous CH$_4$ emission from the targeted area around KRS by itself was not enough to explain all the recently observed variability in the global CH$_4$ concentration growth. In addition, no anomalous CH$_4$ emission was observed around DEM.

4. Conclusions

We calculated the daily CH$_4$ flux with measured concentrations of CH$_4$ and CO$_2$, and the terrestrial biosphere CO$_2$
flux from the CASA ecosystem model. The calculated CH$_4$ flux from the middle taiga around KRS and DEM in WSL from 2005 to 2009 showed a maximum in July. Although anomalously high flux was observed in June and July 2007 and August 2009 at KRS, only a small variation in the flux at DEM was observed. These results indicated that the variation in CH$_4$ flux from the Siberian wetlands was not uniform in space and time. The strength of the calculated CH$_4$ flux could be changed if anomalous weather condition leads to an extreme increase/decrease in CO$_2$ flux from vegetation respiration, but an assessment of this uncertainty requires a better estimation of CO$_2$ flux that includes yearly variation.

Using VISIT, the ecosystem model in which the dimension of the flooded area was 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 could have resulted from the high precipitation rate. The shortcomings of our approach stemmed from the fact that the values assigned to the variables (such as water table depth) influencing the CH$_4$ flux were not based on the site-specific measurements, but on a general ecological characterisation of the region. In order to reduce the uncertainty in our model estimation of the CH$_4$ flux, we need to constrain the model calculation using actual observational data.

5. Acknowledgements

We would like to thank Sergey Mitin (Institute of Microbiology, Russian Academy of Sciences) for administrative support. We also express our sincere thanks to Yasunori Tohjima (NIES) for providing us with fruitful comments on flux calculation. Kaz Higuchi (York University) is acknowledged for the critical reading of the manuscript and for English language corrections. This research was supported by the Global Environment Research Account for National Institutes of the Ministry of the Environment, Japan, through its funding of the project titled: Estimation of CO$_2$ and CH$_4$ Fluxes in Siberia using Tower Observation Network.

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