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Atmospheric Chemistry and Physics Discussions

Interactive comment on "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" *by* M. Sasakawa et al.

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Comment; Why do you assume "zero annual mean (CO2) flux" for an area dominated by peatlands (page 27763, lines 12-14)? Can you exclude reduced CO2 emissions under the high precipitation situation in summer 2007?

Reply; There could be yearly variation for CO2 flux as well. However, no validated data for CO2 flux over Siberia since almost no other continuous observed concentration data exist during the period. Furthermore, temporal variation of CH4 is generally supposed

to be much larger than that of CO2. So as the first attempt, we calculated CH4 flux assuming no yearly variation for CO2 flux. However, we take into account the daily variation based on the daily meteorological fields from reanalysis data. We have added the following paragraph in the conclusions: "The strength of the calculated CH4 flux could be refined if anomalous weather condition leads to an extreme increase/decrease in CO2 flux from vegetation respiration, but an assessment of this bias requires a better CO2 flux distribution that includes yearly variation. A further research is required for evaluating CH4 flux map more precisely in the future."

Comment; What is the size of the footprint of these measurements compared to the model grid?

Reply; We used the data from the minimum grid size of the CASA ($\sim\pm$120 km) and the observed accumulation data for 7 hours for calculation of CH4 flux. There was no dominant wind direction. The model grid is supposed to be enough larger than the footprint size.

Comment; Similar to my critique regarding the CASA modelling, I agree with reviewer #4 that the CH4 modelling with VISIT should be explained and discussed in much more detail.

Reply; In response to the comment from reviewer #4, we have modified Section 2.3 as shown below: "2.3 Ecosystem model Monthly CH4 fluxes from wetlands were estimated with VISIT (Inatomi et al., 2010; Ito, 2010) to evaluate the variation of gas fluxes responding to weather and biological conditions. Fig. 1 shows a schematic diagram of the CH4 exchange processes employed in VISIT. The model consists of carbon, nitrogen, and water cycle sub-schemes, 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,

ACPD
10, C14748–C14760, 2011

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 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 the CH4 emission. Spatial heterogeneity in diffusivity through soil pore spaces is determined on the basis of sand/clay composition data (Hall et al., 2006) and water table 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 μmol liter–1 (Walter and Heimann, 2000). Wetland distribution is determined on a 0.5° $\times$ 0.5° grid based on Global Lakes and Wetland Database (GLWD, Lehner and Döll, 2004) (Fig. 2). 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 $\times$ (finund $\times$ Einund + fdrain $\times$ Edrain) (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 average inundation fraction (finund) is derived from a passive microwave Special Sensor Microwave/Imager (SSM/I) observation for 1993–2000 (e.g., Prigent et al., 2007). Because we estimate the inundation fraction on the basis of seasonal variation for each grid cell, snow cover and extensive flooding after snow melting could in some cases affect the base line. To avoid these apparent variations (e.g., too much severe drying after a spring flood) during the growing-period (May–August), we have decided to use the average inundation fraction derived from the SSM/I ob-

ACPD
10, C14748–C14760, 2011

servation during the period. The baseline water table depths of the inundation and drained wetland surfaces are assumed as 0 and −25 cm, respectively, on the basis of an observation at West Siberian wetlands (Bohn et al., 2007). At layers lower than the water table, CH4 production is estimated as a function of temperature and plant carbon supply, which is obtained from the vegetation production scheme of the model. We also evaluated the influence of precipitation rate on the CH4 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 2001–2009 mean, which was obtained from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). To assess the possible range of estimation, a high (+1mm water table depth/+1mm precipitation anomaly) and a low (similarly, +0.2 mm/+1 mm) response cases were examined. To validate the CH4 flux estimated by VISIT, we compared the model output with a widely used climatological CH4 flux distribution map of the wetlands (bogs, swamps, and tundra) published by the NASA Goddard Institute for Space Studies (GISS) (Fung et al., 1991)."

Comment; The manuscript would benefit from structural changes and in grammatical improvements.

Reply; As shown in acknowledgment, an English native scientist rechecked English.

Comment; The abstract should be rewritten. Page 27760, line 12: Explain the acronym CASA.

Reply; We have modified the abstract as follows: "We have been conducting continuous measurements of CH4 and CO2 concentration on a network of towers located in taiga, steppe, and wetland biomes of Siberia. Here we describe measurements obtained at two forested bog sites, Karasevoe and Demyanskoe, in West Siberia from 2005 to 2009. Although both CH4 and CO2 accumulation (ΔCH4 and ΔCO2) during nighttime (duration of 7 h beginning 21:30 LST) at Karasevoe in July 2007 showed an anomalously high concentration, higher ratios of ΔCH4/ΔCO2 compared with those

ACPD
10, C14748–C14760, 2011

in other years indicate that a considerably more CH4 flux occurred relative to the CO2 flux in response to a large precipitation recorded in 2007 (∼2.7 mm d-1 higher than the climatological 1979–1998 base). Estimated seasonal CH4 fluxes based on the ΔCH4/ΔCO2 ratio and a 3-hourly CO2 flux calculated from a Carnegie–Ames–Stanford Approach ecosystem model for the 2005–2009 period exhibited a seasonal variation with maximum in July at both sites. Annual values of the CH4 emission from the forested bogs around Karasevoe (approx. 7.8×104 km2) calculated from a process-based ecosystem model, Vegetation Integrative Simulator for Trace gases, showed an inter-annual variation of 0.54, 0.31, 0.94, 0.44, and 0.41 Tg CH4 yr-1 from 2005 to 2009, respectively, with the highest value in 2007. It was assumed in the model that the flooded area is proportional to the cumulative anomaly in monthly precipitation rate. Although the emission in 2007 was 2∼3 times higher than those in other years, the anomalous CH4 emission from the targeted area around Karasevoe by itself does not appear to explain all the recently observed variability in the global CH4 concentration growth."

Comment; it does not reference to the CH4 flux studies which have been already conducted in Siberia. Please check for the work of Glagolev et al., van Huissteden et al., Corradi, Merbold et al., Wille, Kutzbach, Sachs et al.,Walter, Zimov et al..

Reply; We had already checked them. However, most of them focused on tundra or permafrost in the northeastern Siberia, which are totally different environment from our studied area.

Comment; In the current "Results and discussion" section, there is also methodological information (page 27766, lines 8-12) which should be moved to the Methods section.

Reply; We have moved them into Section 2.2.

Comment; The conclusions section should be rewritten.

Reply; We have modified the conclusions as follows: "4 Conclusions Methane flux

ACPD
10, C14748–C14760, 2011

from the forested bog regions around KRS and DEM in West Siberia 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 indicate that the variation in CH4 flux from the Siberian wetlands is not uniform in space and time. 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 CH4 flux in the summer of 2007 around KRS resulted from high precipitation rate. Integrated CH4 emissions in a high (low) response case from the forested bogs around KRS ($\pm$ 3° latitude, $\pm$1° longitude; approx. 7.8$\times$104 km2) resulted in 0.54 (0.39), 0.31 (0.34), 0.94 (0.48), 0.44 (0.36), and 0.41 (0.39) Tg CH4 yr-1 for years 2005 to 2009, respectively. Although the emission in 2007 was 2$\sim$3 times greater than those in other years, the anomalous CH4 emission from the targeted area around KRS by itself was not enough to explain all the recently observed variability in the global CH4 concentration growth. No anomalous CH4 emission was observed in 2008 from the forested bog regions. However, the West Siberian wetlands would likely play a significant role in influencing global atmospheric CH4 variation since the area of the Siberian wetlands is approximately 17 times that of the targeted area around KRS which is about 1.32$\times$106 km2 (Sohngen et al., 2005). The strength of the calculated CH4 flux could be refined if anomalous weather condition leads to an extreme increase/decrease in CO2 flux from vegetation respiration, but an assessment of this bias requires a better CO2 flux distribution that includes yearly variation. A further research is required for evaluating CH4 flux map more precisely in the future."

Comment; Page 27761, line 25: "Expanding"? Is it still expanding?

Reply; We have replaced it with "expanded".

Comment; Page 27762, line 6: What is a "semi-climatological" flux?

Reply; We have modified Section 2.2 as shown below: "2.2 Three-hourly CO2 flux

ACPD
10, C14748–C14760, 2011

and CH4 flux calculation We calculated daily CH4 flux with measured concentrations of CH4 and CO2, and "semi-climatological CO2 flux" from a model. The latter variable is obtained as follows. Three-hourly terrestrial biosphere CO2 fluxes were generated from the monthly Net Ecosystem Production (NEP) flux of the Carnegie–Ames–Stanford Approach (CASA) ecosystem model (Randerson et al., 1997) on a $1^\circ \times 1^\circ$ grid using a procedure similar to that of Olsen and Randerson (2004). Whereas Olsen and Randerson (2004) used the National Center for Environmental Prediction (NCEP) as the source of meteorological fields, we used the data from the JMA Climate Data Assimilation System (JCDAS; Onogi et al., 2007). First, the 3-hourly downward shortwave radiation was calculated by fitting the 6-hourly JCDAS data to a theoretical clear-sky solar radiation function. Then the 3-hourly Gross Primary Production (GPP) within each month was estimated by distributing the monthly GPP (Net Primary Production (NPP)$\times$2) according to the radiation data. Thereafter, the monthly respiration (Re) is distributed within each month according to: Re(t) = Re,0 $\times$ Q10((T(t)-T0)/10) (1) where Q10 was set at 1.5 and T was obtained from 2-m JCDAS temperature. Then, Re,o was adjusted so that the monthly NEP (GPP-Re) approached the same values as the original CASA NEP data, with zero mean annual biospheric flux at every grid point (i.e., a neutral biosphere flux). In order to estimate the actual daily CH4 flux from the CASA 3-hourly CO2 flux normalized with the observed CH4 and CO2 accumulation on a certain day (day x), we used the average of three midnight data between 20:00 LST (day x) and 5:00 LST (day x+1) as CO2 flux (FCO2). Daily CH4 flux was then calculated with the following Equation: FCH4 = FCO2 $\times$ ΔCH4/ΔCO2. (2) Here we define gas accumulation (ΔCO2 and ΔCH4) as the measured concentration difference between the concentration at 21:30 LST and the elevated concentration at early next morning (4:30 LST). The CH4 flux calculated from this Equation reflects averaged emissions from the surface inside the targeted rectangular area around each tower. 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 nighttime (e.g. Hargreaves and Fowler, 1998, Long et al., 2010). However, the elevated CH4 flux

ACPD
10, C14748–C14760, 2011

during the daytime was not always observed (Long et al., 2010) and it has been shown that, at some wetlands, a diurnal cycle of CH4 flux was not observed (Werner et al., 2003; Rinne et al., 2007)."

Comment; Page 27762, line 14: What do you mean with "a marshy lake"?

Reply; We have replaced "marshy".

Comment; Page 27762, line 20: Please give some indications on measurement principle and precision of the sensor.

Reply; The methane system was originally developed by Suto and Inoue (2010). We have added the following sentence in Section 2.1. "Measurement precision was $\pm$0.3 ppm and $\pm$3 ppb for CO2 and CH4, respectively (Sasakawa et al., 2010)."

Comment; Page 27762, line 26: Is 17 minutes of pumping needed to flush the sample cell? Or why the average of only 3 minutes of concentration data is taken as representative for the 1 h period?

Reply; The flow rate is 35 cm3 min-1. It is necessary time to flush the sample cell and to stabilize CH4 sensor. As written in Section 2.1, the air-sampling flow path is rotated every 20 min, so we can get one averaged data for each inlet per hour.

Comment; Page 27763, lines 9-11: Which variability was generated? And how exactly? Generally, more information on the CASA modelling is needed (see General Comment II.).

Reply; As already shown, we have modified Section 2.2 and added the necessary explanation.

Comment; Page 27764, lines 19-20: Rephrase this sentence. There is also respiration during daytime.

Reply; We have added "respiration".

ACPD
10, C14748–C14760, 2011

Comment; Page 27764, lines 22-23: Do you have measurements or literature references which support this statement for the typical wetlands in the investigation sites? CH4 emission from some wetlands can show strong diurnal variability.

Reply; We have added some references as follows: “For CH4, whose emission from wetlands is relatively steady during the day (Werner et al., 2003; Rinne et al., 2007; Long et al., 2010) or higher during the daytime (Hargreaves and Fowler, 1998; Long et al., 2010) in the summer, the development of NBL and the lowering of the mixed layer (ML) height are the major factor contributing to the nighttime buildup of its concentration, and thus causing the observed diurnal variation.”

Comment; Page 27766, lines 8-12: This belongs to the Methods section.

Reply; We have moved this into Section 2.2.

Comment; Page 27775, Fig. 3: This important figure is very difficult to read. Data symbols are much too small.

Reply; We have modified Figure 3 (It is new Figure 4).

Comment; Page 27759, title: Please use consistently CH4 or methane. Specify if you mean high CH4 concentration or high CH4 emission.

Reply; We have used “CH4” and added “flux”.

Comment; Page 27760, lines 21-23: I suggest rewording: “Atmospheric CH4 is the second most important greenhouse gas after CO2 and plays and important role in atmospheric photochemistry.” Are the photochemical reactions of CH4 the reason for it being the second most important greenhouse gas?

Reply; We had modified it based on the suggestion from reviewer #2 as follows: “Atmospheric CH4 is the second most important anthropogenic greenhouse gas after CO2 because of its influence on the Earth’s radiation budget through infrared absorption and its role in the photochemistry of the atmosphere.”

ACPD

10, C14748–C14760, 2011

Comment; Page 27760, line 26: Remove “some”.

Reply; We have removed it.

Comment; Page 27761, lines 2-3: Use articles “the”: “The long-term trend. . .”, “. . .in the global CH4 content. . .”. I will not list all the many missing articles “the” or “a” in the paper. Please check it yourself.

Reply; We have added articles.

Comment; Page 27761, line 28: Please write more precise: “ CH4 concentration” instead of just “CH4”.

Reply; We have added “concentration”.

Comment; Page 27763, line 26: “drainage” does not fit here.

Reply; We have removed it.

Comment; Page 27764, line 2: Explain acronyms. “SSM/I”?

Reply; We have added “passive microwave Special Sensor Microwave/Imager (SSM/I)”.

Comment; Page 27764, line 5: “drainage” does not fit here. These areas were not drained, or?

Reply; We have replaced “drainage” with “drained”.

Comment; Page 27764, line 6: remove hyphen: “water table depth”

Reply; We have removed it.

Comment; Page 27764, line 18: Write more precise: “CO2 and CH4 concentrations”

Reply; We have modified it accordingly.

Comment; Page 27764, line 21: A concentration cannot be amplified.

ACPD

10, C14748–C14760, 2011

Reply; We have replaced “concentration” with “accumulation”.

Comment; Page 27764, lines 25-26: What do you mean with “ML... is seasonally pronounced...” Please rephrase.

Reply; We have modified it as follows: “ML height over Siberia is clearly dependent on the season, varying from 200–600 m in the winter to as much as 2800 m in the summer (Lloyd et al., 2002).”

Comment; Page 27765, line 25: A concentration does not accumulate.

Reply; We have replaced “accumulated” with “elevated”.

Comment; Page 27766, line 22, Insert comma after “KRS”.

Reply; We have modified it accordingly.

Interactive comment on Atmos. Chem. Phys. Discuss., 10, 27759, 2010.

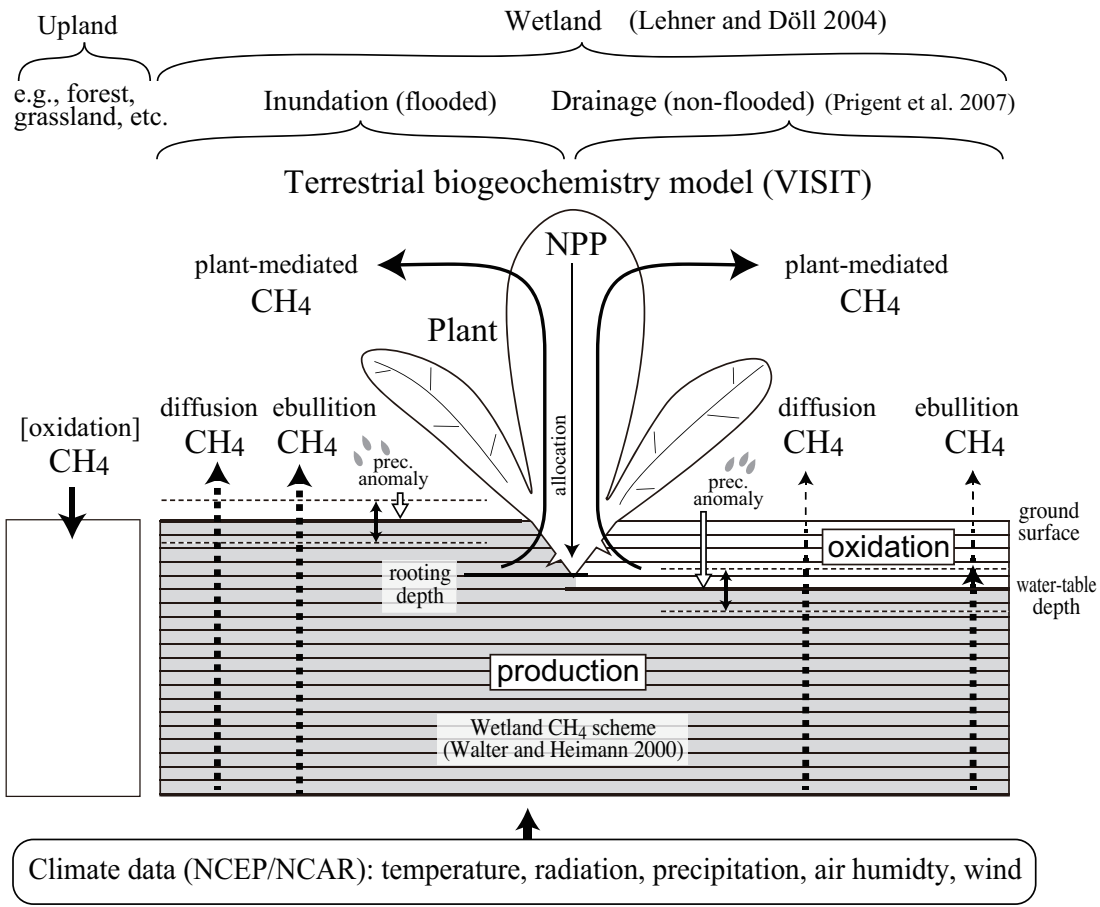

Fig. 1. A schematic diagram of the CH4 exchange scheme used in this study.

ACPD
10, C14748–C14760, 2011

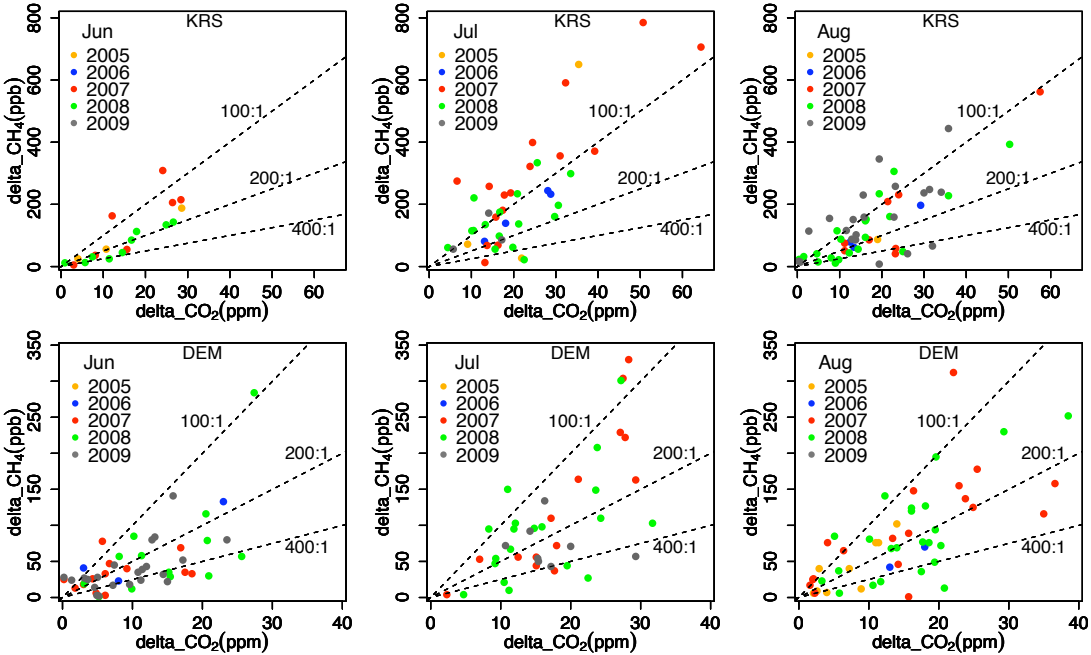

Fig. 2. New Figure 4: Relationship between ΔCO2 and ΔCH4 during summer at KRS (upper panels) and DEM (lower panels).

ACPD
10, C14748–C14760, 2011