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Evaluation of methane emissions from West Siberian wetlands based on inverse modeling

H-S Kim^{1,2}, S Maksyutov², M V Glagolev³, T Machida², P K Patra⁴,
K Sudo⁵ and G Inoue¹

¹ Research Institute for Humanity and Nature, 457-4 Motoyama, Kamigamo, Kita-ku, Kyoto 603-8047, Japan

² National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

³ Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119991, Russia

⁴ Research Institute for Global Change/JAMSTEC, 3173-25 Showa-cho, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan

⁵ Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

E-mail: heonsook.kim@gmail.com

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Abstract

West Siberia contains the largest extent of wetlands in the world, including large peat deposits; the wetland area is equivalent to 27% of the total area of West Siberia. This study used inverse modeling to refine emissions estimates for West Siberia using atmospheric CH₄ observations and two wetland CH₄ emissions inventories: (1) the global wetland emissions dataset of the NASA Goddard Institute for Space Studies (the GISS inventory), which includes emission seasons and emission rates based on climatology of monthly surface air temperature and precipitation, and (2) the West Siberian wetland emissions data (the Bc7 inventory), based on *in situ* flux measurements and a detailed wetland classification. The two inversions using the GISS and Bc7 inventories estimated annual mean flux from West Siberian wetlands to be 2.9 ± 1.7 and 3.0 ± 1.4 Tg yr⁻¹, respectively, which are lower than the 6.3 Tg yr⁻¹ predicted in the GISS inventory, but similar to those of the Bc7 inventory (3.2 Tg yr⁻¹). The well-constrained monthly fluxes and a comparison between the predicted CH₄ concentrations in the two inversions suggest that the Bc7 inventory predicts the seasonal cycle of West Siberian wetland CH₄ emissions more reasonably, indicating that the GISS inventory predicts more emissions from wetlands in northern and middle taiga.

Keywords: West Siberian wetlands, wetland CH₄ emission, *in situ* flux measurements, inverse modeling

1. Introduction

The amount of atmospheric methane (CH₄), a potent greenhouse gas, is again increasing after maintaining a near zero growth rate from 2000 to 2006. There was a large global increase in 2007, especially at northern latitudes. The cause of the 2007 increase is still uncertain, but wetland CH₄ emissions

enhanced by high temperatures in northern regions and greater than average precipitation in the tropics are potential contributors (Dlugokencky *et al* 2009, Bloom *et al* 2010). CH₄ emissions from wetlands constitute the largest single source of CH₄ (IPCC 2001) and play an important role in the interannual variation in the global CH₄ budget (Bousquet *et al* 2006). CH₄ production from anaerobic bacterial decomposition in

wetlands depends highly on soil temperature and the water table (Walter *et al* 2001a); thus, climate-induced changes in wetland emissions have been investigated (e.g., Walter *et al* 2001b, Shindell *et al* 2004). However, while wetland CH₄ emissions have been estimated, their global distribution and magnitude remain largely uncertain.

Matthews and Fung (1987) published a global database of wetland CH₄ emissions with a 1° resolution for five major wetland types, compiling independent data on vegetation, soil properties, and fractional inundation. The total CH₄ emissions from the derived global wetlands, which have an area of $\sim 5.3 \times 10^{12}$ m², were estimated to be ~ 110 Tg yr⁻¹ using typical emissions rates for the five wetland types based on limited field measurements and a simple assumption for the emission seasons at different latitudes. Aselmann and Crutzen (1989) published another global distribution of wetlands with a 2.5° latitude by 5° longitude grid, compiling published information and data from various maps for six simplified wetland types. From the derived global wetland area of $\sim 5.7 \times 10^{12}$ m², global CH₄ emissions were estimated to be 40–160 Tg yr⁻¹ using the geometric mean of the measured emissions rates for each wetland type and the emission seasons determined by temperature or inundation. The estimate of Aselmann and Crutzen (1989) for 50–70°N was roughly one third of the CH₄ estimate of Matthews and Fung (1987), but included higher CH₄ emissions for the southern tropics. These studies suggest that the global wetland distribution is a major contributor to the large uncertainty in emissions estimates due to different classifications of wetland types and spatial extrapolation of emissions rates based on limited field measurements for typical wetland types.

The world's largest extent of wetlands occurs in West Siberia, where wetlands account for 27% (6.85×10^{11} m²) of the area of West Siberia (Peregon *et al* 2009). These extensive West Siberian wetlands contain 40% of global peat deposits (Walter 1977) and play a significant role in the global carbon cycle as a large carbon sink and a major natural source of atmospheric CH₄ (Smith *et al* 2004). Moreover, the large amounts of soil carbon deposited in permafrost regions may be released under a warmer climate. Anisimov (2007) projected that by 2050 the annual net CH₄ flux from Russian permafrost regions may increase by 6–8 Tg yr⁻¹, of which 2.2–3.3 Tg yr⁻¹ will come from West Siberia, depending on future climate scenarios. The significance of West Siberian wetlands to the global carbon cycle has been recognized, but our understanding of CH₄ emissions estimates from West Siberian wetlands and their spatial and temporal distribution has been inadequate. Recently, Glagolev *et al* (2010) published CH₄ emission data for West Siberian wetlands at a 0.5° resolution, based on *in situ* flux measurements for each bioclimatic zone and a detailed wetland classification. In their updated version, the estimated wetland CH₄ emissions of West Siberia were 3.2 Tg yr⁻¹, which is about half the value of wetland CH₄ emissions published in Fung *et al* (1991).

In this study, we estimate West Siberian wetlands CH₄ flux through inverse modeling using our wetland CH₄ emissions inventory based on Glagolev *et al* (2010). Despite a much larger amount of chamber flux observations included in the

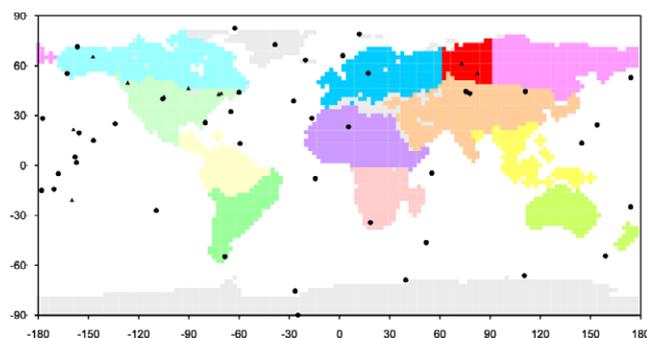


Figure 1. Map of the 12 land regions and the locations of the measurement sites used in this study. The black circles indicate surface-level atmospheric CH₄ observations and the black triangles are vertical profiles.

recent inventory, there is still a significant degree of uncertainty in the emission rates and seasonality, thus validation and correction by comparing to the atmospheric observations are needed. Airborne observations of CH₄ at two sites over West Siberia are used to adjust the magnitude of West Siberian CH₄ flux with inverse modeling: at Surgut over wetlands in middle taiga and at Novosibirsk in forested steppe. Another inversion is performed using wetland CH₄ emissions in Fung *et al* (1991) with a different spatial distribution from our inventory. The two inventories are evaluated by comparison between observed and predicted CH₄ concentrations in two inversions at the two sites located in the middle and the south of West Siberia. Inverse model-estimated fluxes are used to evaluate and correct the amplitude and phase of the seasonal variation of wetland CH₄ emissions.

2. Methods and data

2.1. Inverse modeling

We use the time-dependent Bayesian inversion applied in the TransCom 3 experiment, which assessed the influence of different transport algorithms on CO₂ inversion (Gurney *et al* 2004). The Bayesian inversion minimizes the differences between the modeled concentrations TF (T represents transport) and the observed concentrations x and between the predicted flux magnitudes F and their prior flux magnitudes F_0 . A cost function (J) to be minimized is defined as

$$J = \frac{1}{2}[(TF - x)^T C_x^{-1} (TF - x) + (F - F_0^T) C_{F_0}^{-1} (F - F_0)] \quad (1)$$

where C_x and C_{F_0} are covariance matrices for the observations and prior flux estimates, respectively. In this study, we invert a seasonal cycle of atmospheric CH₄ observations to optimize the monthly CH₄ flux magnitudes for 12 land regions (figure 1) and two CH₄ flux categories. The individual CH₄ surface sources are classified into two CH₄ flux categories: anthropogenic sources from fossil fuels, waste treatment, and ruminant animals and natural sources from biomass burning, wetlands, rice paddies, termites, and soils.

In forward simulations, the individual monthly CH₄ surface sources for each region are emitted for a single month

and then discontinued for the remainder of the 6 yr simulation to consider the response of CH₄ transport, using interannually repeating OH levels and winds for the analysis year. The National Institute for Environmental Studies (NIES) transport model (Maksyutov and Inoue 2000) simulates 288 tracers for CH₄, representing a combination of the 12 land regions and 12 months for two CH₄ flux categories. The off-line model has a 2.5° × 2.5° horizontal resolution and 15 vertical layers up to 20 km in altitude and is forced by the 12-hourly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay *et al* 1996) with a semi-Lagrangian transport algorithm. The chemical destruction of CH₄ by OH, which is the main CH₄ sink, is included in forward simulations, without considering the stratospheric sink. We use monthly OH fields predicted by the chemical atmospheric general circulation model for study of atmospheric environment and radiative forcing (CHASER) (Sudo *et al* 2002), which was developed to simulate the tropospheric photochemistry involving the O₃–HO_x–CH₄–CO photochemical system and the oxidation of non-methane hydrocarbons. The mean lifetime of tropospheric CH₄ predicted in the forward simulations was 9.7 years, which is very close to the value of 9.6 years recommended by the IPCC (2001). We use temporal and spatial distributions from the Emission Database for Global Atmospheric Research (EDGAR) inventory (Olivier and Berdowski 2001) for anthropogenic sources and the global CH₄ emissions dataset of the NASA Goddard Institute for Space Studies (Fung *et al* 1991), called the GISS inventory, for natural sources with individual flux magnitudes from Patra *et al* (2009), but not for wetlands. In this study, we use the magnitudes from the GISS inventory as is for bogs and tundra and scaled up for swamps, and the global wetland CH₄ emissions of 148.9 Tg yr⁻¹ are used.

We invert the monthly mean observations of atmospheric CH₄ during 2002–7 at 52 sites (figure 1) taken from the GLOBALVIEW data product of the NOAA Earth System Research Laboratory. The measurement sites used in this study are those for which the data records are at least 70% complete for 2002–7. Airborne measurements have been made over West Siberia once a month at Surgut and Novosibirsk in good weather since 1993 and the monthly means for 1993–2007 at Surgut and for 1997–2007 at Novosibirsk are added to the inverse modeling. The discrete-level concentrations of the vertical profile are converted into a partial-column concentration up to 4000 m, assuming that each level concentration represents a column concentration with a 1000 m thickness centered at each level to avoid effects by model biases in vertical mixing (Nakatsuka and Maksyutov 2009). We assume a definition of monthly data uncertainties of $\delta_{\text{data}} = \sqrt{\delta_{\text{meas}}^2 + \delta_{\text{mod}}^2}$ for each site, where δ_{meas} is the measurement uncertainty, which is set to 3 ppb for all data (Bergamaschi *et al* 2005), and δ_{mod} is the three-month moving standard deviation between the observed and modeled CH₄ concentrations in the forward simulations. The minimum data uncertainty is set to 6 ppb to avoid a strong effect of certain sites. The prior flux estimates are identical to the CH₄ flux magnitudes used in the forward simulations and the prior flux uncertainties are set to 50% for anthropogenic and natural fluxes.

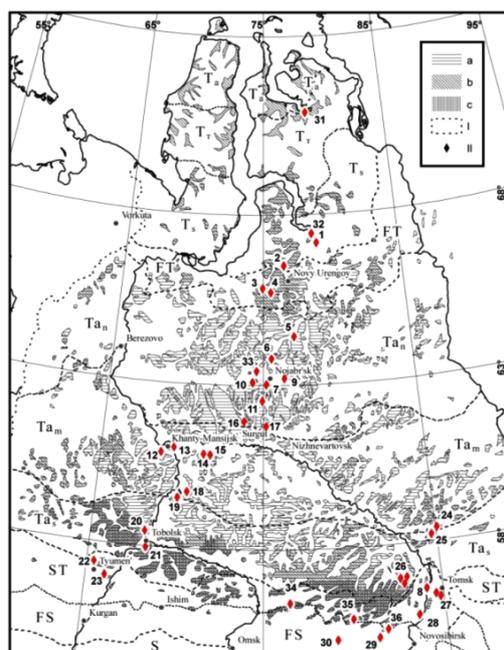


Figure 2. Locations of CH₄ flux measurements and bioclimatic zones in West Siberia. Wetland landscape types of (a) oligotrophic bogs, (b) mesotrophic fens, and (c) eutrophic fens. (I) The bioclimatic zones are Arctic tundra (T_A), typical tundra (T_T), southern tundra (T_S), forest tundra (FT), northern taiga (T_{A,n}), middle taiga (T_{A,m}), southern taiga (T_{A,s}), subtaiga (ST), forest steppe (FS), and steppe (S). (II) The 36 measurement sites.

2.2. CH₄ emissions from West Siberian wetlands

The CH₄ flux from West Siberian wetlands was measured using a static chamber method at 36 sites (figure 2) for eight bioclimatic zones covering all of West Siberia during 2003–9. Glagolev *et al* (2010) published West Siberian wetland CH₄ emissions data at a 0.5° resolution using a statistical emissions model, which includes emission periods for eight bioclimatic zones, a 20 wetland typology map, and emission rate probability density distributions for eight micro-landscape types per each bioclimatic zone, based on *in situ* flux measurements. The detailed wetland classification in West Siberia used in the emissions model was developed by combining high-resolution satellite images and field survey data in Peregon *et al* (2008). Our inventory (called the Bc7 inventory), which is an update of the emissions model in Glagolev *et al* (2010), estimated total West Siberian wetland CH₄ emissions at 3.2 Tg yr⁻¹ and we see a distinct north–south gradient of emissions with strong magnitudes centered in southern taiga (figure 3(a)). The large CH₄ emissions were estimated from oligotrophic hollows, eutrophic fens and ponds in southern taiga. More than half of West Siberian wetland CH₄ emissions were emitted from oligotrophic hollows in taiga zones and from eutrophic fens in southern regions of West Siberia.

By contrast, the GISS inventory estimated strong emissions for the northern and middle taiga, as well as the southern taiga, and the north–south gradient seen in the Bc7 inventory was not apparent (figure 3(b)). The total CH₄

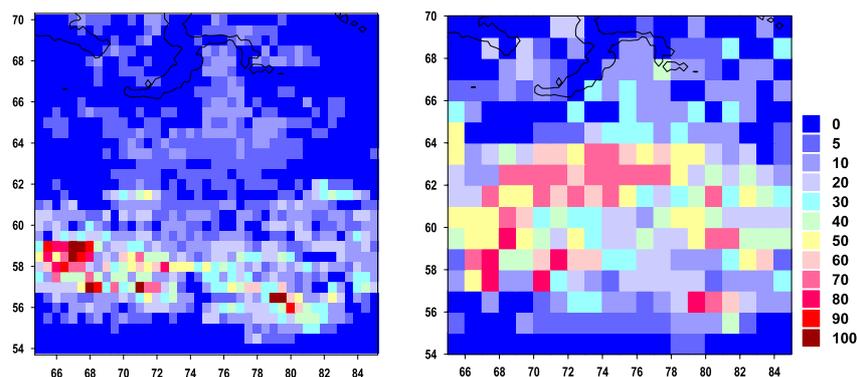


Figure 3. Spatial distribution of the West Siberian wetland CH_4 emissions ($\text{mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$) for July and August in the Bc7 and GISS inventories. (a) 0.5° resolution of the Bc7 inventory; (b) 1.0° resolution of the GISS inventory. The black lines in the figures indicate the shore line.

emissions from West Siberian wetlands were estimated to be 6.3 Tg yr^{-1} , which is about double the estimate based on the Bc7 inventory. The global wetland CH_4 emissions of the GISS inventory were estimated using the emission seasons and emission rates, based on the climatology of monthly surface air temperature and precipitation and the spatial distribution of the five wetland types published in Matthews and Fung (1987). The GISS inventory includes emissions from dry tundra. The emission rates were assumed to be temperature-regulated for forested and non-forested bogs concentrated between 50°N and 70°N , while for forested and non-forested swamps, alluvial formations and dry tundra, a constant emission rate during the emission seasons was assumed for each wetland type, based on limited flux measurements for typical wetland types (Fung *et al* 1991). The large emissions difference between the Bc7 and GISS inventories may be caused by different emission rates in northern and middle taiga: higher emission rates were assumed in the GISS inventory as compared with the Bc7 inventory.

3. Results and discussion

Atmospheric CH_4 is predominantly oxidized by reacting with OH, and OH concentrations have a significant effect on the seasonal cycle of tropospheric CH_4 . In the northern hemisphere, high OH concentrations lead to low CH_4 concentrations in the summer. Nevertheless, high CH_4 concentrations were observed in the summer over West Siberia; the CH_4 partial-column concentration (black in figure 4(b)) reached its peak in August at Surgut (61.0°N , 73.0°E) over wetlands in middle taiga, while a very small increase in the CH_4 partial-column concentration (black in figure 4(c)) was seen in the summer at Novosibirsk (55.0°N , 82.5°E) in forest steppe. The high CH_4 concentrations observed in the summer and the decrease in CH_4 concentrations with distance from wetlands indicate the significance of large CH_4 emissions from the vast West Siberian wetlands in the seasonal cycle of CH_4 concentrations. The two observations over West Siberia were used to adjust the seasonal cycle of the estimated flux of West Siberia in inverse modeling. In this study, two inversions were performed using two different CH_4 emissions from West Siberian wetlands: Case 1 used CH_4 transport and prior fluxes

from the EDGAR and GISS inventories, and Case 2 was the same as Case 1, but used the Bc7 inventory for wetland emissions in West Siberia.

The estimated annual mean West Siberian wetland CH_4 fluxes were 2.9 ± 1.7 and $3.0 \pm 1.4 \text{ Tg yr}^{-1}$ for Cases 1 and 2, respectively. Although the two inversions use different prior fluxes, their results showed considerable agreement on flux estimates and the seasonal cycle, indicating the robustness of inverse modeling on flux estimates. The estimated flux in Case 1 was much lower than the prior flux of 6.3 Tg yr^{-1} (GISS inventory) and the monthly estimates deviated from the uncertainty range of the prior flux throughout the emission seasons (blue and black in figure 4(a)). The large adjustment in Case 1 to the prior flux with the large flux uncertainty reduction (37.9%) during the emission seasons implies that the GISS inventory predicted more wetland CH_4 emissions over West Siberia. By contrast, the estimated flux in Case 2 was very similar to the prior flux of 3.2 Tg yr^{-1} (Bc7 inventory) and the estimated seasonal cycle resembled the prior flux, with a small flux uncertainty reduction (8.6%) during the emission seasons and no large departures from the prior flux (red and gray in figure 4(a)). Figures 4(b) and (c) compare predicted partial-column CH_4 concentrations up to 4000 m with observations at Surgut and Novosibirsk. The inversion of Case 2 predicted the monthly variation in CH_4 concentrations and fitted the observations as a whole rather well, implying that the seasonal cycle of estimated flux is well constrained. Although the Case 2 inversion resulted in higher concentrations than the observations at Novosibirsk, the departures from the observations fell within the range of data uncertainty. The prior seasonality according with the estimated seasonality in Case 2 suggests that the Bc7 inventory predicted the seasonal cycle of CH_4 emissions from West Siberian wetlands reasonably well.

The estimated seasonal cycle in Case 1 resembled the Case 2 estimate, but with more emissions in September. The seasonality of the estimated flux is refined by data constraints, but its spatial distribution follows that of the prior flux. The predicted concentrations in Case 1 were higher than those observed at Surgut, which led to a larger than observed concentration gradient between the two sites. Unlike the predicted concentrations in Case 2, which were close to the

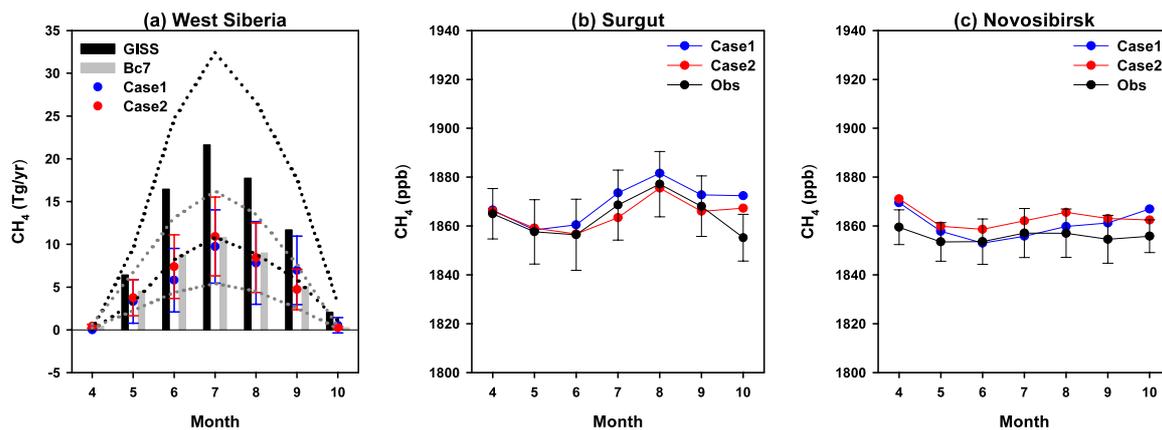


Figure 4. (a) Prior and estimated wetland CH₄ fluxes in West Siberia during the emission seasons. The black and gray boxes are the prior fluxes from the GISS and Bc7 inventories, respectively, with the flux uncertainties (dotted lines); the red and blue circles are the estimated fluxes in Cases 1 and 2, respectively, with the flux uncertainties (error bars). The observed and predicted partial-column CH₄ concentrations up to 4000 m at (b) Surgut and (c) Novosibirsk during the emission seasons. Black, observed concentrations with data uncertainties for the averages in Cases 1 and 2 (error bars); red and blue, the predicted concentrations in Cases 1 and 2, respectively.

observed values at Surgut, the higher concentrations predicted in Case 1 at Surgut imply that more emissions from wetlands in northern and middle taiga of West Siberia were predicted in the GISS inventory, indicating that high emission rates were assumed for wetlands in northern and middle taiga. This also suggests that the Bc7 inventory, based on *in situ* flux measurements and the detailed wetland map, predicted more reasonable emissions from wetland in northern and middle taiga. At Novosibirsk in forest steppe, the predicted concentrations in Case 1 increased after August, in contrast to the observed pattern. This may also indicate the influence of emission rates for swamps/alluvial formations in the south of West Siberia which were assumed to have a constant monthly value for each wetland type in the GISS inventory: the constant emission rates during emission seasons may provide a reason for the uncertainties in the seasonal prediction of emissions from swamps/alluvial formations. The inversion of Case 2 described the seasonal variation of observations at Novosibirsk reasonably well, but higher concentrations were predicted in Case 2 than those observed. The higher concentrations at Novosibirsk predicted in Case 2 led to a smaller than observed concentration gradient between the two sites and this means that the Bc7 inventory predicts more emission from wetlands in southern taiga and subtaiga, indicating the necessity of reducing the emissions. The greater emissions from wetlands in southern taiga and subtaiga could be adjusted through an updated version of the emissions model used in the Bc7 inventory, lessening the large north–south gradient of wetland emissions.

4. Conclusions

The seasonal cycle of CH₄ flux from West Siberian wetlands was estimated in inverse modeling using airborne observations over West Siberia to evaluate the seasonal variation and the spatial distribution of wetland CH₄ emissions in two different emissions inventories. The inversion results showed that the Bc7 inventory, based on *in situ* flux measurements and a detailed wetland classification, described the seasonal cycle

of West Siberian wetland CH₄ emissions reasonably well, but suggested that it needs to adjust the north–south gradient. The inverse model suggests downward correction of the GISS inventory in summer by almost half. The overestimation could be attributed to the use of simplified wetland typology and the lack of *in situ* data in the GISS inventory. From these results, we can confirm the importance of *in situ* flux measurements and a detailed wetland classification in uncertainty reduction of emission estimates. Based on the detailed information for West Siberian wetlands, the Bc7 inventory provides more a reliable estimate of the spatial and temporal distribution of West Siberian wetland emissions, thus it can be useful in assessment of the role of West Siberian wetlands in the current increase of atmospheric CH₄ as well as the interannual variation of the global CH₄ budget. Further improvements in regional flux estimates can be achieved by more accurate wetland typology mapping, extending the seasonal and spatial coverage of surface flux measurements and atmospheric concentration observations.

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