Regional methane emission from West Siberia mire landscapes

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Abstract
Methane emissions from mires in all climate–vegetation zones of West Siberia (forest steppe, subtaiga, south taiga, middle taiga, north taiga, forest tundra and tundra) were measured using a static chamber method. The observed fluxes varied considerably from small negative values in forested bogs and palsa to hundreds of mgC m$^{-2}$ h$^{-1}$ in ponds and wet hollows. Observed data were consolidated in the form of the empirical model of methane emissions designated as the ‘standard model’. The model is based on medians of CH$_4$ flux distributions of eight different micro-landscape types depending on their location and estimated duration of methane emission period within the climate–vegetation zone. The current version (Bc8) of the ‘standard model’ estimates methane flux from West Siberia mires at $2.93 \pm 0.97$ Tg CH$_4$ yr$^{-1}$ that accounts for about 2.4% of the total methane emission from all mires or 0.7% of global methane emission from all sources.

Keywords: methane emission, mires, micro-landscapes, regional flux, West Siberia

1. Introduction
Atmospheric methane produces the second-largest radiative forcing among the long-lived greenhouse gases after CO$_2$. Therefore, estimation of the relative contribution of different methane sources to the atmospheric concentration of CH$_4$ is an important task in addressing the problem of global warming. Since wetlands are considered to be the major natural sources of methane, accurate estimation of its emissions at regional scale is required (Fung et al 1991, Takeuchi et al 2003).

Substantial progress in estimating the sources and sinks of CH$_4$ has been made through combining local observations of CH$_4$ emissions with land unit inventories or other relevant statistical information (Mikaloff-Fletcher et al 2004). West Siberian wetlands belong to the biggest wetland area in the world and contribute essentially to the global methane emission. The area of West Siberia’s mires (Peregon et al 2009) comprises approximately 12.9% of the global peatlands area (Matthews and Fung 1987). Since the earlier estimations of methane flux from West Siberian mire landscapes varied considerably from 2 to 22 Tg CH$_4$ yr$^{-1}$ (Andronova and Karol 1993, Panikov 1995), the regional methane flux from these ecosystems still needs to be assessed more accurately.

Aiming at the reliable estimation of the regional emission from West Siberian mire systems, a long-term and large-scale investigation was organized. The objectives for the study were:

- to determine values of methane fluxes from the different types of West Siberian mire micro-landscapes;
- to determine the relative contribution of these ecosystems to the regional flux;
- to estimate the regional methane flux total from West Siberia mire landscapes.
Results of our study have been partially published in an incremental way in Glagolev (2008), Glagolev and Kleptsova (2009) and Glagolev et al (2010), but this study is the first comprehensive report summarizing all the available data. Glagolev et al (2010) reported the methane emission observation database for all climate–vegetation bands of West Siberia and a model of the methane emissions based on the database is referred to as the ‘standard model’ version Bc5. Kim et al (2011) used an updated version of the model, designated as Bc7, for an inverse model based estimation of the regional methane emissions; however, no details about the construction of the Bc7 version were presented in Kim et al (2011). This study focused on providing a description of the methane emission observation database and a corresponding model of the methane emissions. The current version (designated as Bc8) constitutes a major update to the version Bc5 reported by Glagolev et al (2010), which documents the database only partially. The current version (‘Bc8’) is constructed on the basis of about 2000 individual CH₄ flux measurements (for comparison, the ‘Bc7’ model used in Kim et al (2011) is based upon 1080 measurements).

2. Materials and methods

2.1. Description of research sites

The field observations were carried out during 2007–10 summer–autumn periods. Methane fluxes were measured in representative mire landscapes within a series of key sites distributed over the West Siberian plain (figure 1).

Selection of the key sites was performed using the Landsat 5 TM satellite images with high spatial resolution for 2006–8. Different mire types were recognized using the combination of fourth, fifth and third Landsat channels by their spectral intensity and a structure of pixel clusters. Available cartographic materials (Romanova et al 1977, Matukhin and Danilov 2000) and other published data (Liss et al 2001) were also used. Finally, mire landscapes of 36 key sites distributed in seven zones were chosen for further investigations.

Many of the study sites have already been described in the literature: ‘Pangody’ (Repo et al 2007), ‘New Urengoy’, ‘Pangody-Khasyrej’, ‘Noyabrsk-Palsa’, ‘Noyabrsk-RHLC’, ‘Noyabrsk-Denna’, ‘Noyabrsk-Hills’, ‘Ort’yagun’ (Glagolev et al 2009), ‘Mukhrino’ (Bleuten and Filippov 2008), ‘Shapsha’, ‘Lempino’, ‘Surgut’, ‘Dem’yanka’ (Kleptsova et al 2010), ‘Panikov Mokh’ denoted as ‘Panikov mire’ in Glagolev and Shnyrev (2008), ‘Belyi Yar’ denoted as ‘Ket’-Chulymskoe’ in Glagolev and Shnyrev (2008), ‘Plotnikovo’ in Maksyutov et al (1999), ‘Obskoe’, ‘Tarmany’, ‘Muldashi’, ‘Tagan’, ‘Baturino’ (Glagolev et al 2010).

In addition the following key sites were studied:

(1) ‘Tazovsky’ (67.1°N, 78.9°E). This site is located 35 km south-south-east from the Tazovsky settlement in the tundra zone. This territory is covered evenly by poor fens and bogs. Palsa complexes cover small areas. Wet sedge–cotton grass–sphagnum bogs, sedge–hypnum poor fens and drained thermokarst lakes are widely spread at poorly drained watersheds. Measurements were obtained at ombrotrophic hollows and mire lakes.

(2) ‘Purpe’ (64.46°N, 77.07°E). This key site is located in a watershed flat-palsa complex 20 km east from the Purpe settlement in the north taiga zone. About one half of the total complex area is occupied by numerous lakes. Measurements were made at the lakes and ombrotrophic hollows.

(3) ‘Poikovsky’ (60.88°N, 71.75°E). This key site is situated in the middle taiga zone 15 km south-west from the Poikovsky settlement. Measurements were carried out at the secondary mire lakes. The mean depth of peat layer was about 3 m. The site belongs to the Salym–Yugan mire system.

(4) ‘Agnan’ (61.5°N, 75.0°E). This key site is located 80 km north from Surgut city in the middle taiga zone near the boundary with the north taiga zone. The mire complex represents ancient waterlogged meanders of the Agan River with the peatland area about 80% of the territory. Typical ridge–hollow complexes and ryams (forested raised bogs with dwarf pine–shrub–sphagnum communities) are dominant. Measurements were made in poor fens dominated by sedges (Carex chordorrhiza, C. limosa), horsetails, buckbeans and mosses.

(5) ‘Vakh’ (59.7°N, 70.4°E). This key site is located on the terrace of the Dem’yanka river in the middle taiga zone and represents a mire complex of rich underground water nutrition. Mineralized groundwater outflow areas are occupied by narrow stripes of fens and poor fens (with a size of about 3 × 25 km²). These stripes are dominated by buckbeans, sphagnum and hypnum mosses. Peripheral vegetation consists of birch, ferns (Thelypteris palustris) and hypnum (Tomentypnum nitens) moss. Fens and poor fens are changing to an ombrotrophic mire system with a sequence of ryams and ridge–hollow complexes to the south part of the region.

(6) ‘Tobolsk’ (58.4°N, 68.1°E). This key site is situated 30 km north from Tobolsk City in the south taiga zone and represents large watershed wetland. Round areas of ryams are sequencing with ombrotrophic ridge–hollow complexes and poor fens at the area. Poor fens often dominated by sedges and hypnum moss correspond to the mineralized groundwater outflow areas. Coniferous swamps are widespread at the periphery of the complex. The ratio of ombrotrophic hollow and poor fen areas usually is about 3:2.

(7) ‘Kachipovo’ (57.9°N, 68.2°E). This key site is situated 25 km south from Tobolsk City in the south taiga zone. The mire complex represents a relict floodplain of the Irtysh River now occupied by poor fens dominated by sedges and hypnum mosses accompanied by patterned fen complexes. Raised forested bogs (more than 3 km in diameter) cover the central part of the complex. The peripheral part is occupied by patterned fen complexes which are changing to birch and coniferous swamps.

(8) ‘Kuznetskiy Ryam’ (55.17°N, 81.32°E). This key site is located 100 km west from Novosibirsk city in the forest-steppe zone. The wetland system represents a combination of ombrotrophic raised bogs (ryams) and different fen types typical for this territory. Measurements were made at the reed mire and mire lake.
Figure 1. Key sites of methane emission measurements. Dominant mire type: (a) ombrotrophic mires, (b) poor fens, (c) fens. I. Boundaries of different West Siberian climate–vegetation subzones: Ta—Arctic tundra; Tt—typical tundra; Ts—south tundra; FT—forest-tundra; Ta—north taiga; Tam—middle taiga; Ta—south taiga; ST—subtaiga; FS—forest-steppe; S—steppe. II. Key sites: 1—’Tazovsky’, 2—’New Urengoy, 3—’Pangody’, 4—’Pangody-Khasyrei’, 5—’Purpe’, 6—’Noyabrsk-Palsa’, 7—’Noyabrsk-RHLC’, 8—’Obskoe, 9—’Noyabrsk-Denna’, 10—’Noyabrsk-Hills’, 11—’Or’t-yagun’, 12—’Mukhrino’, 13—’Shapsha-Chistoe’, 14—’Lempino’, 15—’Polkovsky’, 16—’Surgut’, 17—’Agan’, 18—’Vah’, 19—’Dem’yanka’, 20—’Tobolsk’, 21—’Kachipovo’, 22—’Tarmany’, 23—’Maldush’i’, 24—’Panikov Loh’, 25—’Belyi Yar’, 26—’Plotnikovo’, 27—’Tagan’, 28—’Baturino’, 29—’Kuznetskiy Ryam’, 30—’Nikolaevka’, 31—’Gyda’, 32—’Yasavey’, 33—’Noyabrsk-Ridge’, 34—’Usmanka’, 35—’Kreschenskoe’, 36—’Skala’.

(9) ‘Nikolaevka’ (55.15°N, 79.05°E). This key site situated 50 km south-east from Barabinsk town is typologically close to ‘Kuznetskiy Ryam’ wetlands. Measurements were made at the ombrotrophic ryam (1.5 km over) and peripheral fens.

2.2. Research methods

Flux measurements (a total of about 2000) were made by a static chamber method. The chamber consisted of two parts: (i) a permanent stainless steel square collar (40 cm × 40 cm) with a channel for a water lock and (ii) a removable plexiglas box (30 or 40 cm height). To minimize the changes of chamber temperature, the plexiglas box was covered with reflecting aluminum fabric. Mechanical disturbances of peat layer were minimized by using portable or permanent footbridges.

The air inside the chamber was circulated by the battery-operated internal fan. The bottom of the collar was inserted into the soil to the depth of 10 cm at a time about 15 min before the start of the measurements. Gases were sampled at the times \( t_0 \), \( t_1 \), \( t_2 \) and \( t_3 \) using nylon syringes (‘SFM’, Germany). Exposure times \( \Delta t = t_3 - t_0 \) were chosen corresponding to the micro-landscape type and varied from 21 to 60 min on sites with probably high and low fluxes respectively. Syringes were sealed by rubber stoppers and delivered to the laboratory. The leakage from syringes was also checked in a test experiment: it was found that initial CH\(_4\) concentration of 5 ppm decreased at a rate of 0.02% h\(^{-1}\).

Methane concentrations were measured by a gas chromatograph ‘KhPM-4’ (‘Hromatograf’ Co., Moscow, Russia) with a flame-ionization detector (FID) and column
(1 m) filled by Sofpol at 85 °C with hydrogen as a carrier gas (flow rate 10 ml min\(^{-1}\)) or by a gas chromatograph ‘Crystall-5000’ (‘Chromatec’ Co., Joshkar-Ola, Russia) with an FID and column (3 m) filled by HayeSep Q (80–100 mesh) at 70 °C with nitrogen as a carrier gas (flow rate 30 ml min\(^{-1}\)).

At each site the following environmental characteristics were measured: air and peat temperatures (at depths of 0, 5, 15, 45 cm) by temperature loggers ‘TERMOCRON’ iButton DS 1921–2 (DALLAS Semiconductor, USA), pH and electroconductivity by Combo ‘Hanna Instruments’, USA) and concentration of dissolved oxygen by ‘Ecotest-2000’ (‘ECONYX’, Russia). Botanical descriptions were also made.

Methane fluxes were calculated from linear regression with the weights (Kahanaer et al 1989) for the chamber headspace CH\(_4\) concentration versus measuring time. Non-parametric estimations of the density functions for methane flux probability were obtained by the equal-probability interval histograms method.

Received data were consolidated using the ‘standard model’ concept of methane emission described in more detail in Glagolev et al (2010). All varieties of wetland types were reduced to eight micro-landscape types: palsas, ryams, ridges, fens, poor fens, ombrotrophic hollows, peat mats and wetland ponds. The ‘standard model’ is a set of typical emission rates and its periods for the above-listed micro-landscape types in all West Siberia natural zones. The methane emission from the area was estimated by multiplying the average emission rates of the mire micro-landscape types with the area coverage of each of these ecosystems, and the period of methane emission in each zone:

\[
F = \beta \sum_{k=1}^{l} F_k = \sum_{i=1}^{n} f_{ik} S_{ik} T_k,
\]

where \(\beta\)—the scalar coefficient for conversion from mgC yr\(^{-1}\) to TgC yr\(^{-1}\) (\(\beta = 10^{-15}\)); \(F\) (TgC CH\(_4\) yr\(^{-1}\))—the regional methane flux from West Siberian mires; \(F_k\) (mgC CH\(_4\) yr\(^{-1}\))—methane flux from natural zone of type \(k\) \((k = 1–8); k = 1—steppe, 2—forest-steppe, 3—subtaiga, 4—south taiga, 5—middle taiga, 6—north taiga, 7—forest tundra, 8—tundra); \(S_{ik}\) (m\(^2\))—the area coverage of mires of type \(i\) in zone \(k\); \(T_k\) (h yr\(^{-1}\))—the period of methane emission from mires in zone \(k\), derived from seasonal cycle observations by Maksyutov et al. (1999); \(\alpha_{ijk}\)—the area percentage of micro-landscape of type \(j\) in mires of type \(i\) in zone \(k\) by Peregon et al. (2009). \(f_{ik}\) (mgC CH\(_4\) m\(^{-2}\) h\(^{-1}\))—surface density of methane flux in zone \(k\) from mires of type \(i\) \((i = 1, 2, \ldots, n, n = 20)\)—based on the typology of West Siberian mire types according to Romanova et al. (1977) as estimated from digitized maps by Peregon et al. (2009). \(\psi_{ijk}\) (mgC CH\(_4\) m\(^{-2}\) h\(^{-1}\))—median of methane flux from micro-landscape of type \(j\) \((j = 1, 2, \ldots, m, m = 8); j = 1—peat mats, j = 2—palsa, j = 3—ridges, j = 4—ombrotrophic hollows, j = 5—poor fens, j = 6—fens, j = 7—ponds, j = 8—ryams) in mires of type \(i\) in zone \(k\).

3. Results and discussion

Typical methane fluxes from different mire micro-landscape types are presented in figure 2. Since there was still a lack of information for several ecosystems, it was necessary to use certain assumptions for the regional flux calculations. For instance, data about methane fluxes in ponds of forest steppe and subtaiga were combined with those in the south taiga zone; fluxes at steppe mires were extrapolated from nearby northern zones (e.g. in forest steppe).

Methane emission rates vary substantially among the individual micro-landscape types. Palsas, ryams and ridges have the lowest methane fluxes, which are commonly close to zero. Water table levels in these micro-landscapes are usually about 40 cm below surface; as a result methane consuming bacteria in an aerobic layer reduce emission rates. These ecosystems are not of the greatest importance even on a regional scale: covering vast areas of 44% of all West Siberia mires they account only for 11% of the regional CH\(_4\) flux from this territory.

Figure 2. Medians of methane emission from different micro-landscape types of West Siberia mires (error bars denote the interquartile range from first to third quartiles).
Greater rates of methane emission are observed at wetter micro-landscapes such as hollows, fens and poor fens. These ecosystems appear to be the major regional source of methane from wetlands accounting for about 70% of the total CH₄ flux from them. Fens contribute the most in the northern and southern zones because of the large area. At the same time ombrotrophic hollows contribute the most in a central part of West Siberia (see figure 3).

Ponds and peat mats also make an important contribution (19.2%) to the regional flux. The largest fluxes reaching hundreds of mgC CH₄ m⁻² h⁻¹ were observed just in the same landscapes. Such emission rates are not in contradiction with some other publications. For example, the methane production rate of 112 mgC CH₄ m⁻² h⁻¹ was detected in Baltic ponds as reported in Dzyuban (2002). Fluxes from thaw lakes at Chersky reach the rate of 300 mgC CH₄ m⁻² h⁻¹ according to reports by Walter et al (2006).

Increasing soil temperatures to the south favor both methanogenic and methanotrophic microorganism activities. But methane consumption occurs only in a thin aerobic layer (limited from below by the water table level). So higher temperatures cause an initial growth of methane fluxes southwards (see figure 2). On the other hand the total amount of precipitation is decreased to the south, which leads to the reduction of wetland areas and consequently to the smaller contribution of those to the regional methane flux. These two processes overlap with each other in the south taiga zone, resulting finally in the most powerful natural source of methane among all zones in West Siberia (see figure 4).

The main result of the study is a spatially resolved model of methane source distribution within different West Siberia climate–vegetation zones (see figure 5). These emissions are mostly contributed by the taiga zone: north, middle and south taiga yearly emit into the atmosphere 0.55, 0.53 and 1.13 TgC CH₄, respectively. The current version (Bc8) of emission model estimates the total flux from all West Siberia mires at 2.93 ± 0.97 or 3.91 ± 1.29 Tg CH₄ yr⁻¹.

At first sight the total emission calculated in Kim et al (2011) is slightly lower (3.0 ± 1.4 Tg CH₄ yr⁻¹). As both estimates have their uncertainties, and the difference is well inside the uncertainty range, they are not contradicting each other.

When comparing our estimates with the results of Kim et al (2011) we should also take the methane sink by upland forest soil into account. West Siberia CH₄ soil sink can be roughly estimated by simple methods described in Born et al (1990), Dorr et al (1993) and Dutaur and Verchot (2007). In these methods different rates of average annual CH₄ consumption are assigned to different ecosystems. We used the approach of Dutaur and Verchot (2007) in which methane consumption depends on the natural zone, ecosystem type and soil texture. Using soil texture data of Zobler (1986) from the Meeson et al (1995) collection and the vegetation map of Ilyina et al (1976), we estimate average annual CH₄ oxidation at 0.36 ± 0.32 Tg CH₄ yr⁻¹. Thereby our and Kim et al (2011) estimations of total methane flux became closer.

Accordingly, West Siberian wetlands do not appear to be a major contributor to global wetlands emissions as was suggested earlier (by, for example, Panikov 1995). Covering
Figure 4. Methane fluxes from different micro-landscape types within the West Siberia climate–vegetation zones.

Figure 5. Methane source geographical distribution within West Siberia (resolution is 0.5° × 0.5°).

almost 13% of the world mire area they account for only 2.4% of the total methane emission from mires.

Comparable regional emission rates are observed in other regions all over the world. Annual CH₄ emission from natural wetlands with area of 0.3 × 10⁶ km² (Gong et al 2010) in China was estimated to be 1.76 Tg CH₄ yr⁻¹ (Ding and Cai 2007). Methane emission from 1.77 million km² area in the central basin of the Amazon River had a mean of 6.8 TgC yr⁻¹ (Melack et al 2004). Therefore the Amazon River basin, China and West Siberia wetlands give similar fluxes of 5.12, 5.77 and 5.7 g CH₄ m⁻² yr⁻¹ respectively.

Greater emission rates observed in tropical wetlands are related primarily to the period of methane emission continuing almost the whole year. They vary from 16 to 32 g CH₄ m⁻² yr⁻¹ in the Venezuela tropical river floodplain (Smith et al 2000) and reach 12.14 g CH₄ m⁻² yr⁻¹ in the flooded forest zone of the Congo River basin (Tathy et al 1992). Despite lower total emissions on West Siberian wetlands in the present climate, the area vulnerability to global warming requires further research with the focus on both emission rates and mechanistic understanding of the emission processes and their changes in a warming climate.

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