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Assessment of the annual diffusive methane emission from the southern tundra thermokarst lake of Western Siberia

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Abstract. Lakes are among the most important natural sources of greenhouse gas methane (CH_4). Although Western Siberia contains numerous thermokarst lakes, lake CH_4 emissions from this region remain unknown. Here we report the results of field measurements of CH_4 fluxes conducted by static chamber method in summer 2016 on thermokarst tundra lake "Ledyanoe". Based on the measured values, we estimated annual diffusive CH_4 emission from the whole lake by using three approaches: one based on experimental data and two others utilizing modeled data and meteorological records. The quantified annual diffusive CH_4 emission following first method was 135 kg C-CH_4 year^{-1} (97–197 kg C-CH_4 year^{-1} 95% confidence interval), whereas annual CH_4 emission according to next two approaches was 150 kg C-CH_4 year^{-1} (148–151 kg C-CH_4 year^{-1} 95% confidence interval) and 131 kg C-CH_4 year^{-1} respectively. Such convergence between the results of different methods can be attributed to compliance of estimates with real annual emission.

1. Introduction

Methane (CH_4) is one of the most potent greenhouse gases, and lakes are important natural CH_4 sources [1]. Recent assessments [2] suggest that annual net contribution of lakes into global CH_4 emissions equals 30 Tg CH_4 year^{-1} (range: 10–50 Tg CH_4 year^{-1}). In [3] there is an assessment of 8–48 Tg CH_4 year^{-1} given, and in their later work [4] sum of the methane emission from lakes of different latitudes is evaluated as 71.6 Tg CH_4 year^{-1}.Such variability introduces uncertainty in global net lake CH_4 evasion estimates and results in a poor knowledge of CH_4 emissions from lakes on a global scale as well as generally limited understanding of lake CH_4 evasion. Addressing this knowledge gap is therefore imperative, if accurate assessment of lake CH_4 emissions are to be achieved.

In this study we focused on the diffusive component of net CH_4 emissions from thermokarst lakes, since northern lakes are widely understudied, but also because with climate change, CH_4 emissions from northern lakes are expected to rise X-fold (up to 100 Tg CH_4 year^{-1}) over the course of 21 century [2]. Thus, the purpose of this work is to estimate the annual diffuse CH_4 emissions from a thermokarst lake in the southern tundra of Western Siberia using different approaches.

2. Study area

Field measurements of the diffusive CH_4 emissions from the tundra lake "Ledyanoe" (67.3695ºN, 78.6112ºE) were carried out from June 27 to July 4, 2016 in the Tazovsky District of Yamalo-Nenets Autonomous Okrug. The Ledyanoe is a classic thermokarst lake with the area of ≈91400 m^2 (according our estimation using [5]) that currently undergoes shore destruction following permafrost thaw and active peat abrasion. In 2016, the studied area was characterized by the following climatic parameters: mean annual air temperature (MAAT) of –4,9 ºC, mean air temperatures of January and July of –19,9 ºC and 18.6 ºC respectively, mean annual precipitation of 384 mm·$year^{-1}$, frost-free period of 116 days, and period with stable snow cover of 205 days [6]. Trend in Figure 1 shows that, according to data from Tazovsky meteorological station [7], MAAT has been increasing at a rate of 0.03 ºC $year^{-1}$ over past decades. It should be also mentioned that the mean air temperature in July has been increasing at a similar rate of 0.03 ºC $year^{-1}$, whereas for January the rate is substantially lower and equals 0.01 ºC $year^{-1}$ [7].

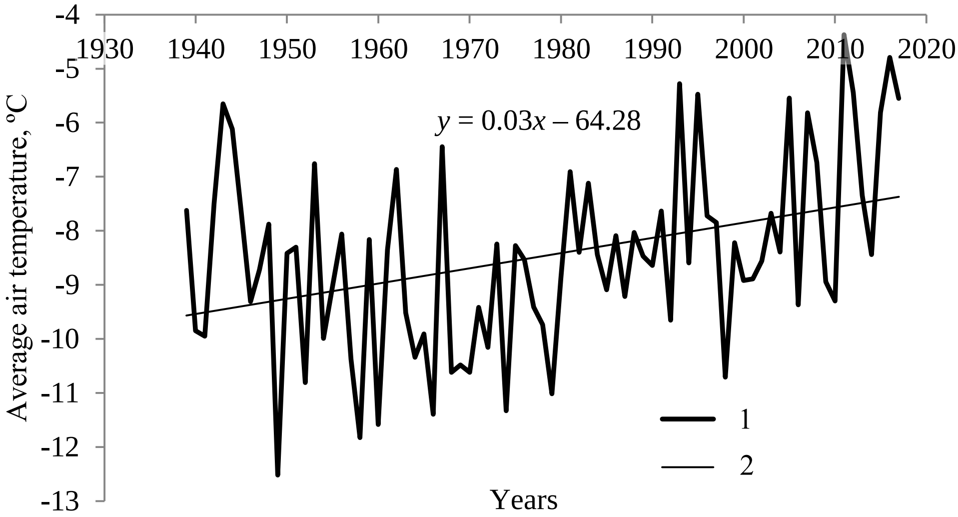

Figure 1. MAAT in Tazovsky during 1939–2017 (1) and its linear trend (2).

3. Materials and methods

CH_4 fluxes were measured by a static chamber method [8] on the lake surface at sampling locations with different water depth. The diurnal CH_4 dynamics were measured in the littoral zone of the lake (the shallowest area) every two hours in two replications (Table 1).

Table 1. Sampling points of CH_4 fluxes from lake Ledyanoe.

Date	Lake part	Water depth, cm	Number of measurements	Time of measurements
June 27	center	170	8	16:34–20:05
July 02	between center and shore	170	8	16:03–18:18
July 02	shore	50	8	19:44–21:34
June 03–04	shore	75	23	14:17–12:37 (diurnal dynamics)

We deployed plexiglass chambers (40 cm × 40 cm × 40 cm size) equipped with floats and covered with reflective tape to minimize surface heating. Each chamber was deployed for 30 minutes, during which 4 gas samples of chamber air were taken at regular intervals, starting from the moment the chamber was placed on water. The samples were transferred into glass vials filled with concentrated NaCl solution and transported to the laboratory for later analysis. CH_4 concentrations were determined in triplicates on gas chromatographer using Chromatec-Crystal 5000.2 (ZAO Khromatek, Yoshkar-Ola) equipped with a flame ionization detector and N_2 as a carrier gas. Calibration of the chromatograph was carried out using standard gas mixtures with the known CH_4 concentrations: 0.49 ± 0.07 ppm, 5.3 ± 0.5 ppm, 10.3 ± 0.6 ppm, 100 ± 5 ppm (OAO Monitoring, St. Petersburg). We calculated CH_4 fluxes by linear regression with weights for positive CH_4 flux values and nonlinear with weights for negative CH_4 flux values. We also measured air temperature near water surface by portable meteorological station Skywatch GEOS N11 (JDC Electronic SA, Switzerland).

We further quantified diurnal dynamics of CH_4 emissions and established quantitative relationship between the CH_4 flux and the time of day as well as air temperature (for details see [9]):

$$F=(0.47\pm0.01)+(0.012\pm0.001)\cdot T_{air}\cdot\sin([\boldsymbol{\pi}\cdot(1.14\pm0.11-h)/24]^2), \quad (1)$$

where F is CH_4 flux (mg C-CH_4 m^{-2} h^{-1}), T_{air} is air temperature (°C), h is running hour, corresponding to the mid-exposure time (hh.hh, integer and decimal fraction). Note that the equation parameters are determined with their standard errors. As for the biochemical ground of the link between CH_4 flux and T_{air}, we suppose that in this case due to the shall depth of the measurement point (0.7 m) air temperature influences a lot water temperature, which, in turn, affects bottom one and intensity of the methanogenesis processes.

We also estimated annual diffusive CH_4 emissions by utilizing 3 different approaches:

- *First method.* We used the "standard model" methodology [10], where one of the parameters is the median CH_4 flux measured in the field was used. As an error of median, 95% confidence interval (CI) was used according to [11]. Another important parameter is the length of CH_4 emission period, derived from air temperature data. In 2016, the length of this period was 134 days [9].
- *Second method.* Using Equation (1) and air temperature records from the Tazovsky meteorological station [6] as the T_{air} parameter, we calculated CH_4 fluxes for each 3 hours from June 3 to October 3, 2016 (since this is the time interval corresponding to the CH_4 emission period for the study site, and temperature on the meteorological station is recorded each 3 hours), assuming the applicability of Equation (1) to the entire temperature range of this period. Then, we used the median value of the modeled CH_4 fluxes as a characteristic parameter for the "standard model" to quantify annual diffusive CH_4 emissions.
- *Third method.* Here we used the same length of CH_4 emission period as in second method, but the CH_4 emission was calculated for each 3 hour-period for the whole lake. Then the sum of all calculated CH_4 fluxes was accepted as an estimation of annual CH_4 emissions from the studied lake.

4. Results

Table 2 shows results of the CH_4 fluxes quantified based on direct field measurements and the modeled values.

Table 2. Statistical characteristics of the CH_4 fluxes from lake Ledyanoe.

Data:	Methane fluxes, mg C-CH_4 m^{-2} h^{-1}				
	I quartile	Median	III quartile	Lower limit of 95% CI	Upper limit of 95% CI
measured	0.30	0.46	0.79	0.33	0.67
modeled	0.47	0.51	0.58	0.50	0.52

The “standard model” methodology, which considers median of the measured CH_4 fluxes (0.46 mg C-CH_4 m^{-2} h^{-1}), lake area and CH_4 emission period, has resulted in 135, 97 and 197 kg C-CH_4 $year^{-1}$ annual CH_4 emissions (estimation value, lower and upper limits of its 95% CI respectively).

Calculations of the annual CH_4 emission based on the modeled fluxes using 0.51 mg C-CH_4 m^{-2} h^{-1} following second method resulted in 150 kg C-CH_4 $year^{-1}$ (148–151 kg C-CH_4 $year^{-1}$ 95% CI), while annual CH_4 emission estimated by third method yielded 131 kg C-CH_4 $year^{-1}$.

Narrow CI of the assessment of annual CH_4 emission following second method (difference between upper and lower limits of CI is 3 kg C-CH_4 $year^{-1}$) is not least related to a large number of modeled CH_4 flux values (936 units). This 95% CI is fully included in 95% CI of the CH_4 emissions estimate calculated based on direct measurements (first method). Assessment of the annual CH_4 emission following third method is 131 kg C-CH_4 $year^{-1}$ and is close to 135 kg C-CH_4 $year^{-1}$ quantified using first method.

5. Conclusion

Both estimates of the annual diffusive CH_4 emissions from lake Ledyanoe obtained from the modeled data are consistent with the estimates derived from the “standard model”. This result however needs further validation based on field data from other thermokarst lakes of Western Siberia. If there is a relationship between diffusive CH_4 emissions from lakes and mean air temperature, it will be possible to improve assessments of the annual diffusive CH_4 emissions from Western Siberian lakes using local air temperature data, i.e. derived from meteorological records. Though to obtain a holistic picture of net lake CH_4 emissions other CH_4 emission pathways, as i.e. ebullition, should be included.

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