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 (CH₄). Although Western Siberia contains numerous thermokarst lakes, lake CH₄ emissions from this region remain unknown. Here we report the results of field measurements of CH₄ fluxes conducted by static chamber method in summer 2016 on thermokarst tundra lake “Ledyanoe”. Based on the measured values, we estimated annual diffusive CH₄ 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 CH₄ emission following first method was 135 kg C-CH₄ year⁻¹ (97–197 kg C-CH₄ year⁻¹ 95% confidence interval), whereas annual CH₄ emission according to next two approaches was 150 kg C-CH₄ year⁻¹ (148–151 kg C-CH₄ year⁻¹ 95% confidence interval) and 131 kg C-CH₄ 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 (CH₄) is one of the most potent greenhouse gases, and lakes are important natural CH₄ sources [1]. Recent assessments [2] suggest that annual net contribution of lakes into global CH₄ emissions equals 30 Tg CH₄ year⁻¹ (range: 10–50 Tg CH₄ year⁻¹). In [3] there is an assessment of 8–48 Tg CH₄ 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 CH₄ year⁻¹. Such variability introduces uncertainty in global net lake CH₄ evasion estimates and results in a poor knowledge of CH₄ emissions from lakes on a global scale as well as generally limited understanding of lake CH₄ evasion. Addressing this knowledge gap is therefore imperative, if accurate assessment of lake CH₄ emissions are to be achieved.

In this study we focused on the diffusive component of net CH₄ emissions from thermokarst lakes, since northern lakes are widely understudied, but also because with climate change, CH₄ emissions from northern lakes are expected to rise X-fold (up to 100 Tg CH₄ year⁻¹) over the course of 21 century [2]. Thus, the purpose of this work is to estimate the annual diffuse CH₄ 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” (67.3695°N, 78.6112°E) 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 °C, mean air temperatures of January and July of –19.9 °C and 18.6 °C 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 °C 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 °C year$^{-1}$, whereas for January the rate is substantially lower and equals 0.01 °C year$^{-1}$ [7].

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

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).

| 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. CH₄ concentrations were determined in triplicates on gas chromatograph using Chromatec-Crystal 5000.2 (ZAO Khromatek, Yoshkar-Ola) equipped with a flame ionization detector and N₂ as a carrier gas. Calibration of the chromatograph was carried out using standard gas mixtures with the known CH₄ 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 CH₄ fluxes by linear regression with weights for positive CH₄ flux values and nonlinear with weights for negative CH₄ 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 CH₄ emissions and established quantitative relationship between the CH₄ flux and the time of day as well as air temperature (for details see [9]):

\[ F = (0.47 \pm 0.01) + (0.012 \pm 0.001) \cdot T_{\text{air}} \cdot \sin([\pi \cdot (1.14 \pm 0.11 - h)/24])^2, \]

where \( F \) is CH₄ flux (mg C-CH₄ m⁻² h⁻¹), \( T_{\text{air}} \) 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 CH₄ flux and \( T_{\text{air}} \), 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 CH₄ emissions by utilizing 3 different approaches:
- **First method.** We used the “standard model” methodology [10], where one of the parameters is the median CH₄ 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 CH₄ 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 \( T_{\text{air}} \) parameter, we calculated CH₄ fluxes for each 3 hours from June 3 to October 3, 2016 (since this is the time interval corresponding to the CH₄ 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 CH₄ fluxes as a characteristic parameter for the “standard model” to quantify annual diffusive CH₄ emissions.
- **Third method.** Here we used the same length of CH₄ emission period as in second method, but the CH₄ emission was calculated for each 3 hour-period for the whole lake. Then the sum of all calculated CH₄ fluxes was accepted as an estimation of annual CH₄ emissions from the studied lake.

4. Results
Table 2 shows results of the CH₄ fluxes quantified based on direct field measurements and the modeled values.

**Table 2. Statistical characteristics of the CH₄ fluxes from lake Ledyanoe.**

| Data:     | Methane fluxes, mg C-CH₄ 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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