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METHANE EMISSIONS FROM THERMOKARST LAKES IN THE SOUTHERN TUNDRA OF WESTERN SIBERIA

ABSTRACT. Lakes are an important natural source of methane – significant greenhouse gas of the modern atmosphere. Monitoring of methane emission from lakes of northern territories is needed to update the available estimates of CH4 emission intensity into the atmosphere and to obtain multi-year series of observations. Field measurements of diffuse methane fluxes were carried out on lakes at different stages of thermokarst process located in Yamalo-Nenets Autonomous District (Western Siberia, Russia) during summer 2016 using static chamber method. Some statistical characteristics of measured fluxes were calculated (medians vary from 0.46 to 0.93 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$), as well as annual diffuse emissions from studied lakes, which values are determined by the area of the lake's water surface. Daily dynamics of methane fluxes were defined and approximation of fluxes with simple model was done, major factors are temperatures of lake bottom and of the surface air layer.

KEY WORDS: Greenhouse gases, fluxes, methane, freshwater ecosystems, polar regions

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INTRODUCTION

Methane (CH_4), which is a trace gas of the modern atmosphere, is one of the most important greenhouse gases. One molecule has an impact on the climate 28–34 times greater than CO_2 using a 100-year horizon (IPCC 2013). This, together with feedback mechanism between annual global temperature and CH_4 emission contributing to rapid release of methane from natural sources under climate warming causes the importance of methane studying (O'Connor et al. 2010).

According to assessment given in (Kirschke et al. 2013) the global annual methane emission from natural sources for 2000-2009 varies from 238 to 484 $TgCH_4 \cdot year^{-1}$ and is equal to 44–57% of total methane emission. In the third place among them are lakes with contribution from 10 to 50 $TgCH_4 \cdot year^{-1}$

(Anderson et al. 2010). Thermokarst lakes of Western Siberia tundra zone are of special interest because of their poor exploration degree due to the inaccessibility of the sites and response of subarctic regions to climate change (Pavlov and Malkova 2009).

A characteristic hydrological feature of Western Siberia is the exceptional abundance of lakes. It is associated with a flat topography and aquiclude that occurs close to the surface because of wide permafrost spreading in the northern part of the plain (Shvareva 1963). The total area of lakes in the southern tundra is 8.8 thousands km^2, which is 5% of the total area of the subzone of the southern tundra of Western Siberia (Golubyatnikov and Kazantsev 2013; Golubyatnikov et al. 2015). The boundaries of the southern tundra zone were taken according to (Gvozdetskiy et al. 1973; Liss et al. 2001).

The activity of methane-producing Archaea is regulated by several factors, one of them is the bottom sediment temperature (Schulz et al. 1997). In turn, the temperature of the lake bottom is influenced to a certain extent by the climatic features of the studied region.

The issue of monitoring the lakes as a source of methane of the northern territories of Western Siberia still remains unsolved – previous measurements in this area (Glagolev et al. 2010a; Golubyatnikov and Kazantsev 2013) including small number of lakes (10 objects in total) were conducted in summer season 2009–2010. So further studies are needed to update the available estimates of CH_4 emission from tundra lakes into the atmosphere, as well as to obtain multi-year series of observations.

The aim of our work was to study diffuse fluxes of methane from the lakes of the southern tundra of Western Siberia, to identify factors that affect the emission intensity and to estimate the annual diffuse emission of methane from lakes of different stages of the thermokarst process. In this paper we focused on the study of the diffuse emission of methane at open water period.

STUDY AREA

Field studies of methane fluxes from lakes were carried out from June 27 to July 4, 2016 in the key site «Jarneto» (67.37°N, 78.60°E) 12 km to the southwest from the settlement Tazovsky (Yamalo-Nenets Autonomous District) located in the natural zone of the southern tundra (Fig. 1).

Territory is characterized by moderate continental to continental climate with long severe winter and short cool summer. A characteristic feature of the climate is its significant variability over the years (Vasilevskaya et al. 1986). The average annual air temperature in the zone of the southern tundra in 2016 was -4.9°C, the average air temperature in July and January was 18.6°C and -19.9°C, respectively. The duration of the frost-free period is 116

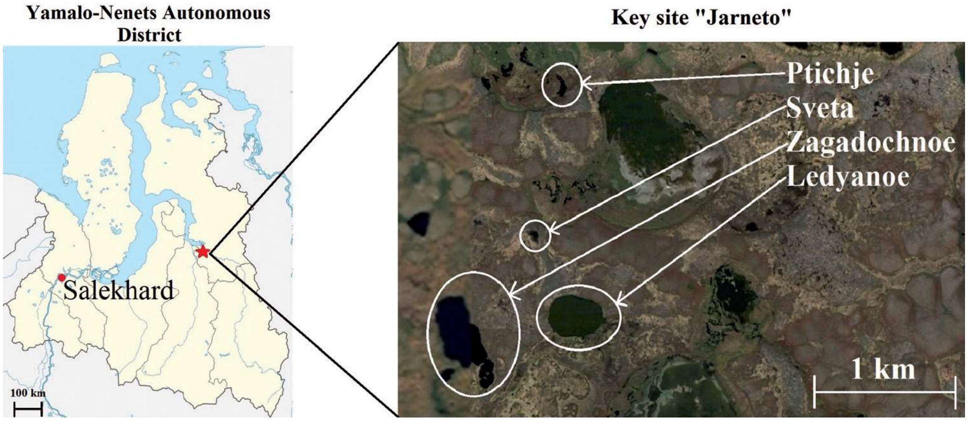

Fig.1. Location of the study site (based on (openstreetmap.org; maps.google.com))

Table 1. Characteristics of studied lakes

Lake	Coordinates, degrees		Area, m^2
	N	E	
Ledyanoe	67.3695	78.6112	≈ 91400
Zagadochnoe	67.3683	78.5925	≈ 131000
Ptichje	67.3841	78.6093	≈ 5100
Sveta	67.3748	78.6044	≈ 1800

days, the amount of precipitation is 384 mm·year^{-1}, the duration of the period with a stable snow cover is 205 days (rp5.ru).

The terrestrial ecosystems of the study area consist of shrubby-lichen tundra in watershed areas and oligotrophic and meso-oligotrophic bogs on slopes and lowland areas according to the classification (Liss et al. 2001). Besides there are khasyreys that are large depressions of the ground surface caused by draining of thermokarst lake.

The study site is located in the northern part of the Pur-Taz interfluve in the zone of continuous permafrost with high ice content (Firsov et al. 1989). According to (Kravtsova 2009), this area belongs to the zone of ubiquitous distribution of medium and large thermokarst lakes of modern and late Holocene thermokarst in peatlands and mineral soils. The studied lakes are located on the third terrace, composed of ice-covered lake-alluvial sediments of the Upper Quaternary age. The satellite images show a polygonal frozen cracks that confirms thermokarst formation of the lakes due to thawing of the underground ice. The location of frozen soils upper boundary under thermokarst forms are the following: within the limits of small lake water bodies (diameter less than 0.1 km), the thickness of talik zones is from 3 to 80 m, under larger lakes – the thickness of taliks is more than 100 m, and under lake basins over 1 km mainly through taliks were formed (Andrianov et al. 1989).

The studied lakes differ in the stage of the thermokarst process. Ledyanoe and Zagadochnoe lakes are in the active phase of destruction of icy margins (Fig. 2), which is a sign of active thermokarst processes and the growth of the lake depression. Ptichje lake is characterized by the initial stage of shallowing, bogging along the shoreline (Fig. 3). Lake Sveta is at the final stage of the thermokarst lake, characterized shallow depth, widespread bogging and weediness of waters (Fig. 4). Some characteristics of studied lakes are given in Table 1.

MATERIALS AND METHODS

The measurements of CH_4 flux were performed using the static chamber method following the methodology described in (Glagolev et al. 2010b). Plexiglass chambers (40 cm × 40 cm × 40 cm) covered with reflecting fabric and floats of four plastic bottles with a capacity of 2 liters were used (Fig. 5). Chambers were dipped into the water with their lower facet being 4 cm below the surface. The period of exposure was 30 min during which 4 gas samples were taken in 50 ml three-component syringes. The air samples were transferred to hermetically sealed glass bottles by displacing the concentrated sodium chloride solution. The temperature was measured at the surface of the lake and at the bottom (thermal sensors «Thermochron» DS 1922L, Maxim Integrated, USA), the wind speed, air temperature and atmospheric pressure at 5 cm above the lake surface (portable weather station Skywatch GEOS N11, JDC Electronic SA, Switzerland) were observed. All these variables along with the depth of the lake were registered at each measurement point. Samples of bottom sediments were taken from Ptichje lake. The methane fluxes measurements for diurnal dynamics on Ledyanoe lake were made in duplicate once every two hours. Table 2 gives a more detailed description of fluxes measurement points.

Fig. 2. Lake Ledyanoe

Fig. 3. Lake Ptichje

Fig. 4. Lake Sveta

Fig. 5. Floating chambers

Table 2. Points of methane fluxes measurements (2016 year)

Date	Lake	Lake part	Water depth, cm	Number of measurements	Time of measurements
27.06	Ledyanoe	center	170	8	16:34–20:05
02.07	Ledyanoe	between center and shore	170	8	16:03–18:18
02.07	Ledyanoe	shore	50	8	19:44–21:34
03.07-04.07	Ledyanoe	shore	75	23	14:17–12:37 (diurnal dynamics)
28.06	Zagadochnoe	center	150	8	14:32–18:53
29.06	Zagadochnoe	between center and shore	140	7	12:37–15:14
29.06	Zagadochnoe	shore	60	8	16:23–18:42
30.06	Sveta	center	90	8	12:09–14:26
30.06	Sveta	shore	82	8	15:43–17:59
01.07	Ptichje	center	120	8	14:05–16:22
01.07	Ptichje	shore, deep place	170	8	17:15–19:23

The methane concentrations in the samples were determined by gas chromatography on a Chromatec-Crystal 5000.2 instrument (ZAO Khromatek, Yoshkar-Ola) with a flame ionization detector. Each sample of gas from a syringe was analyzed three times. The volume of the sampler (loops) is 0.250 ml. The length of the chromatographic column is 3 m, the diameter is 2 mm, the adsorbent is Hayesep-N 80/100. The column temperature is 60°C, the temperature of the flame ionization detector is 150°C. As the carrier gas, nitrogen (99.999%) is used at a flow rate of 30 ml·min^{-1}. The flow rate of hydrogen – 20 ml·min^{-1}, air – 200 ml·min^{-1}. Calibration of the chromatograph was carried out using calibration gas mixtures with the following methane concentrations: 0.49 ± 0.07 ppm, 5.3 ± 0.5 ppm, 10.3 ± 0.6 ppm, 100 ± 5 ppm (OAO Monitoring, St. Petersburg).

Organic carbon concentrations in sediments were determined in the laboratory of UNESCO Chair on Environmental Dynamics and Global Climate Change (Yugra State University) using an EA-3000 analyzer (EuroVector, Italy) by combustion in a catalyst tube in excess of oxygen and helium current. Gas separation was produced in a packed chromatography column and the detection of a signal on a thermal-conductivity detector. Calibration was produced by two standards: acetanilide (C=71.09%, N=10.36%, H=6.71%) and atropine (C=70.56%, N=4.84%, H=8.01%) using a linear calibration method.

The values of fluxes were calculated by the linear regression method with weights for positive values and nonlinear with weights for negative values (Glagolev et al. 2010b).

With the KSDENSITY function from the Statistic Toolbox of Matlab 7.10.0 (MathWorks, USA), probability density functions for methane fluxes were calculated for each lake. The weights of the variables were determined in inverse proportional to the square of the standard deviation corresponding to the measurement, according to (Rumshiskyi

1971); the kernel type (normal) and the smoothing width correspond to the default ones. Boundaries, on which the probability density was reconstructed, were chosen in accordance with arguments in (Krivenok et al. 2014): the interval [min(x_i-w_i); x_{max}+v] was taken, where x_i is measured methane flux, w_i is corresponding error value, i is the index number of measurement (varies from 1 to n), n is the number of measurements; $v=5\cdot(x_{max}-x_{min})/(n-1)$, x_{min} and x_{max} are the minimum and maximum values of measured methane fluxes (according to Stephanyuk's empirical formula, (Vapnik et al. 1984)). For more details on the construction of probability distributions in application to methane fluxes, we refer to (Glagolev and Sabrekov 2008).

For checking of the measured methane fluxes accordance with lognormal distributions the Anderson-Darling test with 0.05 significance level from the Statistic Toolbox of Matlab was used.

The annual diffuse emission of methane was calculated using the methodology of the «standard model» (Glagolev 2008). According to this methodology, the annual diffuse methane emission was calculated as product of the following parameters: 1) area of the lake water surface; 2) the period of diffuse methane emission; 3) characteristic values of methane fluxes (the medians of the measured methane fluxes on each lake) taken by constants during the entire emission period. 95% confidence interval was given as an error of the medians according to (GOST R ISO 16269-7-2004 2004).

The period of diffuse methane emission in 2016 is calculated according to the methodology outlined in (Suvorov and Glagolev 2007). In this work, the period of methane emission (PME) is defined as the duration of the summer-autumn period multiplied by the empirically selected coefficient. The date of a stable transition of the average daily air temperature through 10°C is taken as the beginning of the summer-autumn period. The date of a stable transition of the average daily air temperature through 0°C is taken for the end of it. According to the Tazovsky meteorological station (rp5.ru) in 2016, the summer-autumn period lasted from June 9 to October 3 (117 days). The empirical coefficient required for the calculation of the PME was assumed to be 1.147. This value was obtained by dividing the PME values given in (Glagolev, 2008) to the duration of the summer-autumn period according to the data of (Shvareva 1963) – reference which was indicated in the original publication when describing the PME calculation method. So the duration of PME in the southern tundra in 2016 was selected as 134 days.

Approximation for the daily dynamics of methane fluxes was conducted by the following equation (we were inspired by (Juutinen et al. 2004) for choosing this form of dependence):

$$F = b_1 + b_2 T_{air} \cdot \sin\left(\left[\pi \cdot \left(b_3 - h\right)/24\right]^2\right)$$

where F –CH_4 fluxes (mgC-CH_4·m^{-2}·h^{-1}), b_1, b_2 and b_3 – parameters, T_{air} – air temperature (°C), h – running hour, corresponding to the mid-exposure time (hh.hh, integer and decimal fraction).

The determination of parameters was carried out in the program STATISTICA 7.0 (StatSoft, USA) using the method of least squares, also weights of the variable F (determined in this case in inverse proportional to the corresponding standard deviation) were taken into account. Parameters were determined with their standard errors, p-level<0.05.

The quality of the approximation is indicated by the value of the Theil divergence coefficient, which varies from 0 with a complete coincidence to 1 with a very poor coincidence of the measured and modeled data (Theil 1971).

RESULTS AND DISCUSSION

Following results of field measurements were obtained in 2016: 47 values of methane fluxes from Ledyanoe lake, 16 from lakes Ptichje and Sveta and 23 values from lake Zagadochnoe. The median

Table 3. Statistical characteristics of methane fluxes from the studied lakes of the southern tundra of Western Siberia

Lake	Number of samples	Methane fluxes, mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$				
		I quartile	Median	III quartile	Lower limit of 95% confidence interval	Upper limit of 95% confidence interval
Ledyanoe	47	0.30	0.46	0.79	0.33	0.67
Zagadochnoe	23	0.48	0.59	1.16	0.48	0.86
Sveta	16	0.76	0.93	1.01	0.65	1.12
Ptichje	16	0.16	0.50	2.14	0.16	3.59

values and quartiles were calculated (Table 3). Medians of the methane fluxes from lakes Ledyanoe, Zagadochnoe and Ptichje are approximately 0.5 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$, whereas the median of the methane fluxes from Sveta lake is almost twice higher – 0.96 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$. Probability density functions of methane fluxes for each of the lakes are shown at Fig. 6 a-c.

Probability distributions of methane fluxes from lakes Ledyanoe and Ptichje (Fig. 6 a, b) both have main peaks, which fall on the values 0.25 and 0.10 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$ respectively, Zagadochnoe lake (Fig. 6 a) has peak at 0.48 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$ and another small one near 0.14 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$. The distribution of methane fluxes from lake Sveta (Fig. 6 c) has two peaks, one is near 0.25 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$, the other is 0.94 mgC-$CH_4 \cdot m^{-2} \cdot h^{-1}$.

The Anderson-Darling test does not reject the null hypothesis that measured methane fluxes values for lakes Ledyanoe and Ptichje are from lognormal distributions.

Generally, the lognormal form is quite typical for probability density distributions of the methane fluxes (similar types of distributions could be seen in (Panikov 1995; Smagin et al. 2003; Glagolev and Suvorov 2008). The reason of this phenomenon is described, for example, at (Glagolev and Sabrekov 2008), since it is known that the lognormal value is obtained as the result of multiple multiplications of independent quantities (Borovikov 2001). That means if the studied process is the result of the combined action of several independent processes, then the observed distribution of the random variable is lognormal. This is true for methane emission that consists of the production of CH_4 by microorganisms-methanogens, transport from the place of formation to the surface and consuming by methanotrophs and is influenced by multiple environmental factors (Chanton et al. 1992; Glagolev et al. 2008). With the combined effect of all processes, a distribution close to the lognormal distribution is obtained.

As we can see, on some graphs there are more than one peak. The point is that nowadays the issue of probability distributions errors calculation is not developed completely, particularly Matlab does not have means to estimate these errors. So we can not be confident whether the first (smaller one) peak for Zagadochnoe lake shows real feature of studied ecosystem and not the artifact of mathematical processing of experimental data. But if it is not an artifact and bimodality of methane fluxes probability distribution is a result of natural processes, extrema could be caused by different environmental conditions between measurement points. As for the Sveta lake, it should be mentioned, that there were two measurement points and we can see two major peaks on the graph. This example once again illustrates the fact that it is not correct to use the arithmetic mean of methane fluxes sampling as the distribution of initial data is not normal in most cases (Glagolev and Suvorov 2008; Taylor 1985).

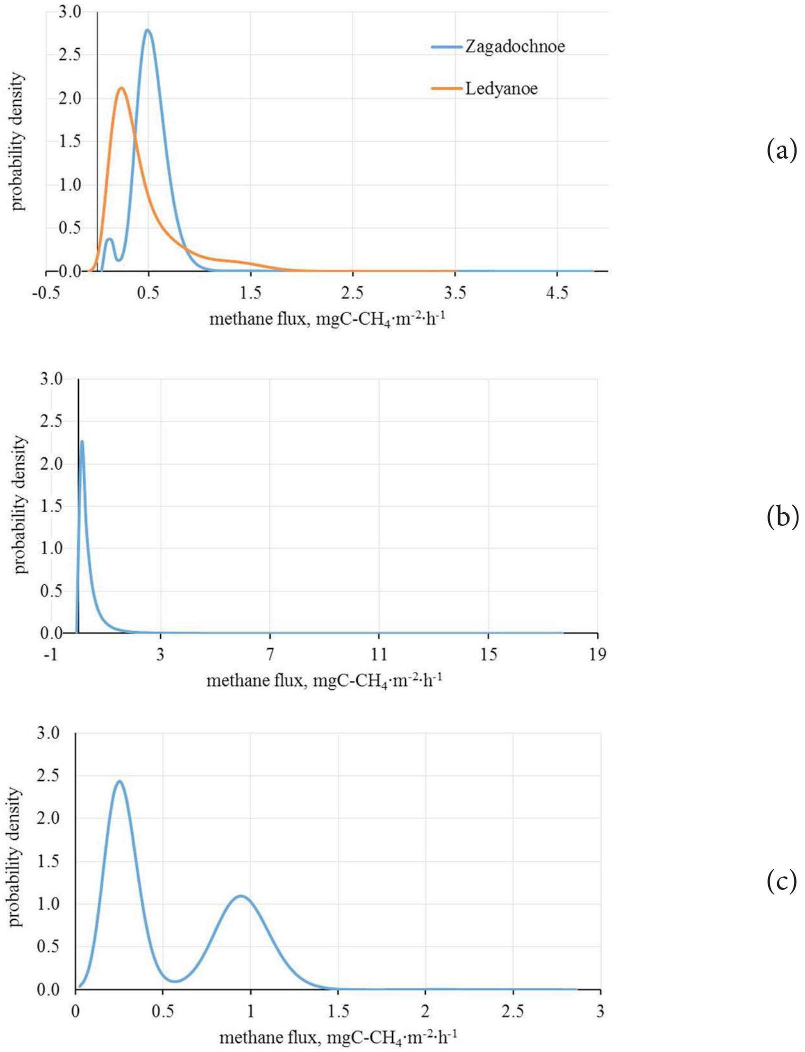

Fig. 6. Probability distributions of methane fluxes from lakes: a) Zagadochnoe and Ledyanoe, b) Ptichje, c) Sveta

We compared the data we obtained with the results of other researchers who conducted similar studies of lakes in various natural zones of Western Siberia (Table 4). Here we should make a restriction that the comparison is not absolutely strict, since the emission of methane is affected by a large number of different factors, the influence of which we can not fully take into account. In the first approximation, we assume that the change of natural zones is an integral factor in relation to most factors that affect methane emission.

As far as we know the first results on emission of methane from the tundra lakes of Western Siberia were published in (Glagolev et al. 2010a). Similar studies (Sabrekov et al. 2011), were conducted in the area of Tazovsky and Gyda (Yamalo-Nenets Autonomous District, Russia). The lakes described in this work, according to our data, are of thermokarst origin, not wetland lakes, as they are classified in the source (one of the authors of this article personally carried out measurements of methane from these lakes). Methane fluxes from the lakes in this research, with the exception of lake Ptichje, exceed the

Table 4. Emission of methane from the lakes of the natural zones of Western Siberia, mgC-CH$_4$·m^{-2}·h^{-1}

Zone	Objects	I quartile	Median	III quartile	Comment	Reference
Southern tundra	Thermokarst lakes	0.32	0.61	0.97	Generalized statistical characteristics are given (calculated from all measured values of methane fluxes)	Current research
Southern tundra	Wetland lakes	0.34	0.64	1.07		Glagolev et al. 2010a
Tundra	Thermokarst lakes	0.15	0.27	0.57		Sabrekov et al. 2011
Forest tundra	Wetland lakes	–	0.17	–	Recalculated from 5.3 mgCH$_4$·m^{-2}·d^{-1}	Repo et al. 2007
North taiga	Wetland lakes	-0.01	0.10	0.31		Sabrekov et al. 2013
Middle taiga	Wetland lakes	–	0.13	–	Recalculated from 4.1 mgCH$_4$·m^{-2}·d^{-1}	Repo et al. 2007
Middle taiga	Small wetland lake		0.75		Recalculated from 24 mgCH$_4$·m^{-2}·d^{-1}	Repo et al. 2007
Middle taiga	Lakes of different types		0.23			Sabrekov et al. 2013
Middle taiga	Wetland lakes	0.18	0.49	2.15		Sabrekov et al. 2013
Southern taiga	Lakes of different types	–	3.08	–	Recalculated from 4.1 mgCH$_4$·m^{-2}·d^{-1}	Sabrekov et al. 2017
Southern taiga	Wetland lakes	3.21	17.94	77.76		Sabrekov et al. 2013
Forest-steppe	Wetland lakes	97.93	125.55	145.92	Quartiles calculated from 4 values	Glagolev et al. 2009

indicated values. This can be explained by the fact that the values of methane from lakes located on the boundary of the typical and arctic tundra were included in the data set (Sabrekov et al. 2011), where the emission is expected to be lower than from the lakes of the southern tundra due to the lower speed of the methanogenesis process.

The methane emissions for thermokarst lakes with three different ages in (Desyatkin 2009) are compared for Eastern Siberia (Central Yakutia) region. Results show the highest emission at «mature alas» stage and the lowest – at «tyympy» one. The stages are named according to the regional classification (Soloviev 1959), where «tyympy» corresponds to the stage of the primary thermokarst lake, and «mature alas» is the stage of lake draining with starting the freezing of the alas depression. Therefore the values of methane fluxes at the primary stage of forming the young thermokarst basin («dyuedya» stage) were comparable with the stage of mature alas. There is an analogy with our studied lakes. Thus, Ledyanoe and Zagadochnoe lakes, which are in the active phase of development, have the values of the methane fluxes 2 times smaller than Sveta lake, that goes through the final stage of development of the thermokarst lake, that is close to the results for Central Yakutia (Destyakin 2009). Nevertheless, Ptichje lake occupies an intermediate position in the development course (going through the initial stage of shallowing), but has the values of methane fluxes equal to Ledyanoe and Zagadochnoe lakes, although the intermediate results are anticipated from the above concept. This can be explained by the fact that lake Ptichje has the largest spread of fluxes values, which is associated with a strong spatial heterogeneity of the methane emission intensity caused by the initial stage of the lake evolution, when some measurements were carried out on a site with developing bogging and others on the open water.

Lakes Ptichje and Sveta can be correlated with wetland lakes according to bottom substrate, that is nutrient medium for methane-producing Archaea, as Ptichje lake sediments contain 10-20% of carbon.

The medians of methane fluxes measured in wetland lakes are reduced in the forest-tundra zone in comparison with tundra lakes and reach a minimum in the north-taiga zone. Further, the values of methane fluxes from wetland lakes increase southward. Thus, methane fluxes from tundra wetland lakes are quantitatively comparable to methane fluxes from more southern middle-taiga wetland lakes. This can be seen as a contradiction, since it is logical to expect an increase in methane emissions from more southern wetlands due to an increase in the intensity of biological processes, in particular, methanogenesis. This phenomenon, as well as the minimum values of methane fluxes from the north taiga wetlands can be explained by a small number of measurements that indicates the need for more detailed studies of methane emissions from lakes of different natural zones of Western Siberia. Besides, in (Glagolev et al. 2009), rather large values of methane fluxes from the wetland lakes of the forest-steppe zone are given. Most likely these values are due to the fact that the researcher was standing on the floating mat and bubbling methane was released, so the methane concentration in the chamber and, correspondingly, the value of the diffuse methane fluxes were overestimated. It should be also mentioned, that in personal communication first author of the article (Sabrekov et al. 2017) explained, that methane flux value of 3.08 mgC-CH_4·m^{-2}·h^{-1} (Table 4) from southern taiga lakes corresponds to total (diffuse plus bubble) methane fluxes. We agree with the suggestion of anonymous reviewer of current article about the increase of bubble CH_4 flux intensity from lakes in southern taiga zone and more southerly regions. Thus, values of methane fluxes for southern taiga and forest steppe are caused both by diffusive and bubble mechanisms of CH_4 transport, whereas for northwardly lakes – mostly by diffuse transport mechanism.

On the basis of measured values of methane emission for each lake, an annual emission was calculated (Table 5).

Table 5. Estimation of annual diffuse methane emissions, kgC-CH_4·$year^{-1}$

Lake	The annual diffuse emission	Lower limit of 95% confidence interval	Upper limit of 95% confidence interval
Ledyanoe	135	97	197
Ptichje	8	3	59
Sveta	5	4	6
Zagadochnoe	249	203	363

The annual emission of methane from lakes varies by almost two orders of magnitude from 5 kgC-CH_4·$year^{-1}$ for lake Sveta to 249 kgC-CH_4·$year^{-1}$ for lake Zagadochnoe. This is primarily due to a significant difference in the areas of the water surface of lakes, whereas the difference in methane fluxes from each lake is insignificant.

Daily dynamics of methane fluxes

The daily dynamics of methane emissions was measured at lake Ledyanoe during the period from 3 to 4 July 2016 (Fig. 7 a). The given plot of the daily dynamics of methane fluxes values has two minimums with an interval of approximately 12 hours: 4 am and 16 pm for shallow

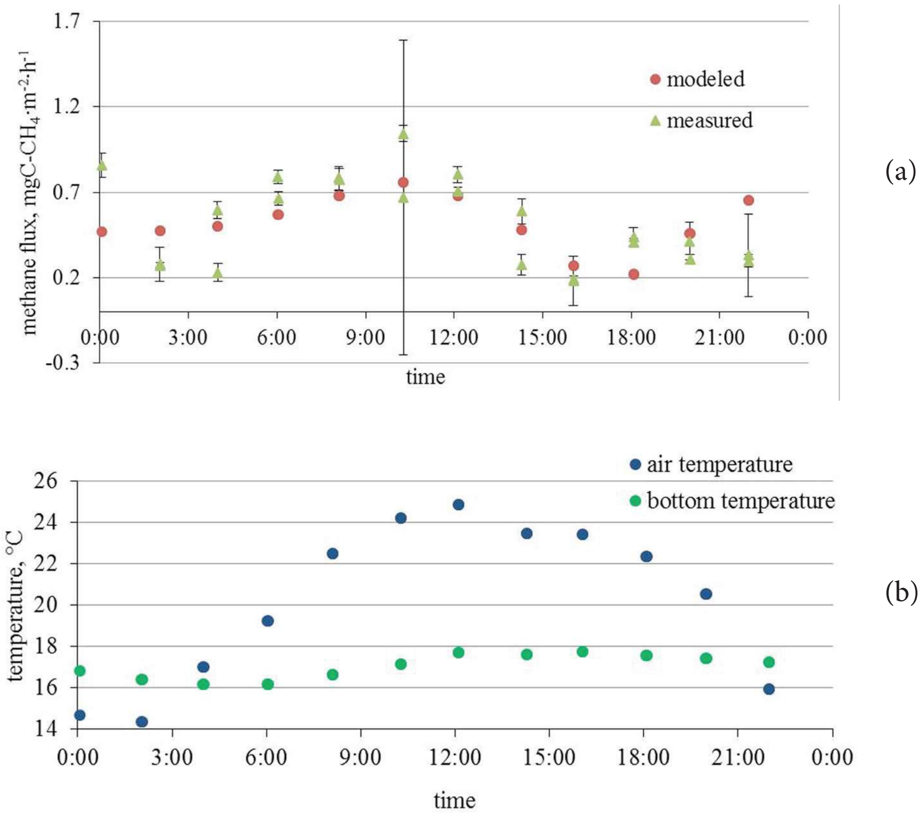

Fig. 7. a) The daily dynamics of methane fluxes for the shallow waters of lake Ledyanoe (July 3–4, 2016). Error bars are for standard deviation. b) Temperatures of lake bottom and air at the surface of the lake

waters of lake Ledyanoe. The only clearly expressed emission maximum is about 10 am.

Thus we obtained the equation (air temperature ranges from 14.4 to 24.9°C) with the following form:

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

For this model Theil divergence coefficient value is 0.03 without contribution of the original data errors and 0.18 with them.

The temperature of the lake bottom correlates nonlinearly with the air temperature T_{air} and with the time of day (Fig. 7 b). The presence of correlations between temperatures is evidenced by the value of the nonparametric rank correlation coefficient of Spearman equal to 0.63. A nonparametric correlation criterion was chosen in view of the fact that the relationship between the variables is nonlinear as advised at (Borovikov 2001).

CONCLUSION

Based on the above results, we made the following conclusions.

Medians of diffuse methane fluxes for the studied thermokarst lakes of the southern tundra vary from 0.46 to 0.93 mgC-$CH_4 \cdot m^{-2} h^{-1}$. The fluxes values from two of studied lakes are of lognormal distributions according to the Anderson-Darling test.

The intensity of methane emission in the shallow part of lakes depends on the temperature of the surface air layer. Due to daily natural fluctuations in air temperature, the daily dynamics of methane emission intensity is also observed.

The annual diffuse emission of methane from the studied thermokarst lakes varies from a few to hundreds of kilograms of methane per year and first of all is determined by the area of the lake's water surface.

This work can be considered as a special case of research in major issue of Western Siberia tundra lakes as a source of methane.

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