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Contribution of Tundra Lakes in Western Siberia to the Atmospheric Methane Budget

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Abstract—The emission of methane from tundra lakes in western Siberia is estimated on the basis of experimental data. According to these estimates, over the warm season, the methane flux from the surfaces of lakes to the atmosphere amounts to 0.5 $KtCH_4$ for Arctic tundra, 2.9 $KtCH_4$ for typical tundra, and 8.5 $KtCH_4$ for southern tundra. The short-term spring emission of methane as ice melts in tundra lakes of the region under consideration is determined with consideration for published estimates of the rate of generation of methane in northern-latitude lakes during the cold season. The contribution made by tundra lakes in western Siberia to the atmospheric methane budget is estimated at 20 $KtCH_4$/year.

Keywords: methane emission, lakes, tundra ecosystems

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INTRODUCTION

One of the organic compounds belonging to trace gases of the earth's current atmosphere is methane. The atmospheric concentration of this gas amounts to about 1770 ppbv and it annually increases, on average, by 0.5–1.0% [1, 2]. The current content of methane in the atmosphere is estimated at 4.6–5.0 Gt, which is about 1.5×10^{-4}% of its volume [1, 3]. The greenhouse potential of methane per one molecule exceeds that of carbon dioxide 21 times. The contribution of methane to the greenhouse effect amounts to about 20% [1, 2]. The yearly mean global radiative forcing of this gas at the atmospheric upper boundary is estimated at 0.48 ± 0.05 W/m^2 [1, 3]. Methane plays an important part in atmospheric photochemical processes and, consequently, it significantly affects the gas composition of the atmosphere [2, 3].

Methane is emitted into the atmosphere from both natural (on average, 208 $MtCH_4$/year) and anthropogenic (on average, 358 $MtCH_4$/year) sources [4]. It follows from the results of experimental studies and model calculations that wetland ecosystems are the basic natural sources of methane [3, 5–7]. Among the natural sources of methane, lakes (whose total area amounts to 4.2×10^6 km^2, or about 3% of the surface area of the continents [8]) rank second in intensity of its emission into the atmosphere [4].

The results of experimental studies showed that methane is emitted from lakes into the atmosphere continuously during the entire period when lakes are free of ice [9, 10]. The intensity of emissions of methane from lakes into the atmosphere depends significantly on the reserves of organic matter at their bottoms: the emission of methane is more intense from lakes whose bottom sediments are rich in organic matter [10, 11]. In lakes of both middle and northern latitudes, the generation of methane goes on also under the ice cover until the frost penetration into lake-bottom sediments is completed. It is noted in [12] that the bottom sediments of many tundra lakes do not freeze in winter and methane is generated in these lakes throughout the year. The methane generated under the ice cover accumulates and is partially trapped in freezing lake ice.

The results of field experiments [13, 14] showed that small (in area) and shallow lakes in the tundra and forests of the temperate zone are characterized by a significantly higher intensity of methane emissions into the atmosphere when compared to large lakes. The methane emission from the open water surfaces of large (over 10 km^2) tundra and forest lakes amounts to 5–17% of that from small lakes. The fluxes of methane from the shallow near-shore zones (1–15% of the total area of a lake) of large lakes are comparable with its fluxes from small lakes.

For tundra lakes in the northern latitudes, the fluxes of methane into the atmosphere range within 2–190 $mgCH_4/(m^2\ day)$ [12, 13, 15]. The emission of methane from lakes in the boreal zone, on average, amounts to 100–300 $mgCH_4/(m^2\ day)$ [4, 16]. Tropical lakes emit methane into the atmosphere with an intensity of 200–400 $mgCH_4/(m^2\ day)$ and more [4]. The global emission of methane from lakes is estimated at 8–50 $MtCH_4$/year [4, 14], which is 4–24% of the global emission of methane from natural sources. It should be noted that the methane emission

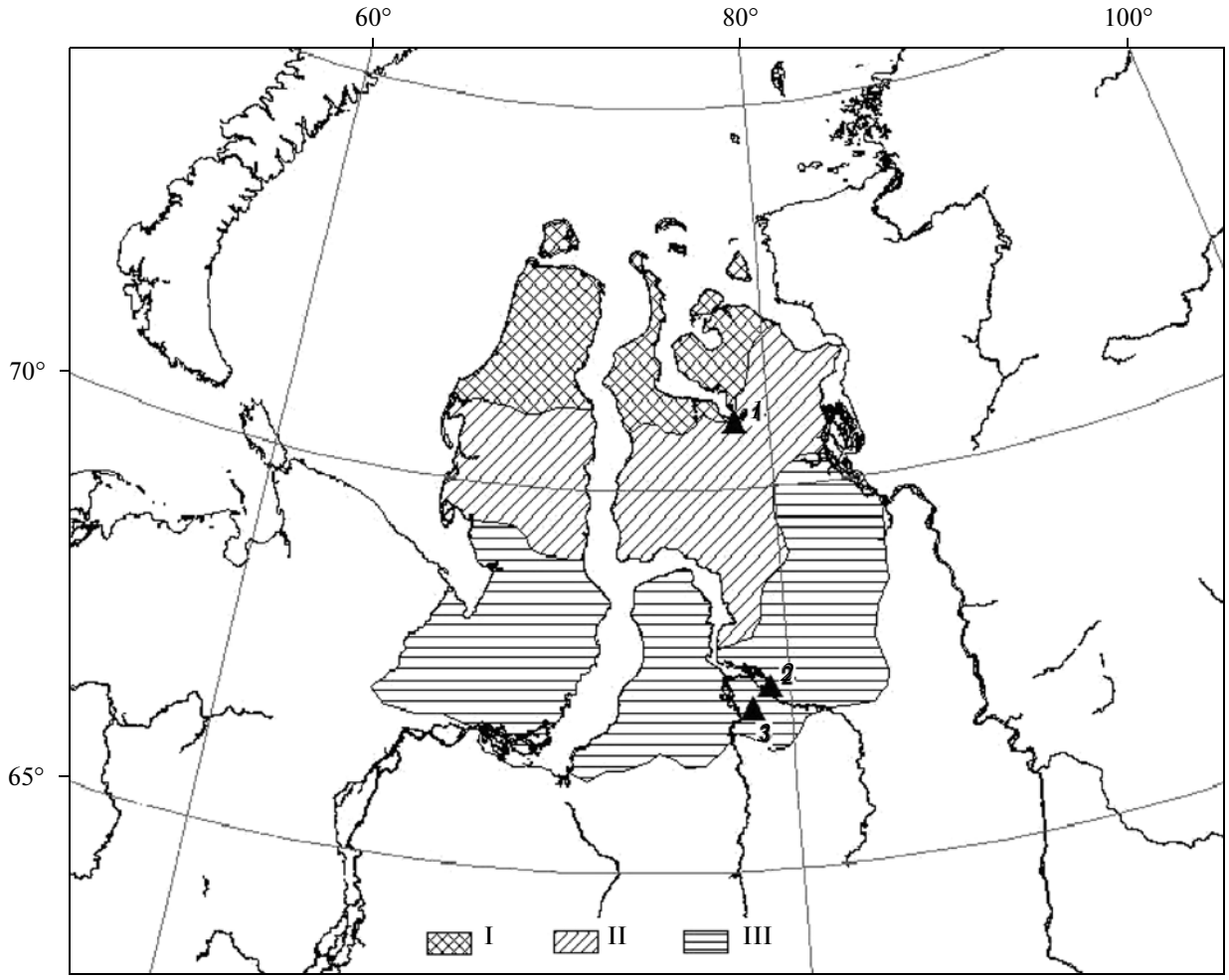


Fig. 1. Phytogeographical zonality of tundras in western Siberia and location of the sites of field observations. Tundra subzones: (I) arctic tundra, (II) typical tundra, and (III) southern tundra. Observation sites: (*1*) Gyda (70°54′ N, 78°32′ E), (*2*) Yasavei (67°35′ N, 78°91′ E), and (*3*) Tazovskii (67°11′ N, 78°55′ E).

from lakes exceeds that from the World Ocean surface, which is estimated at 5–7 $MtCH_4$/year [4, 5].

The biogeochemical processes of generating and oxidizing methane in tundra lakes are as yet not very well studied experimentally. The estimates of methane fluxes into the atmosphere from a number of tundra lakes in Alaska, northern European Russia, and northeastern Russia are given in [12, 13, 17–21]. Many lakes of the tundra ecosystems of western Siberia almost have not been studied as sources of atmospheric methane. There is little published evidence for the fluxes of methane from lakes in this extensive tundra region, which does not allow one to adequately estimate the contribution of the lakes under consideration to either regional or global methane emissions.

In this work experimental data on methane fluxes from the surfaces of lakes in the tundra zone of western Siberia are analyzed and, on their basis, the contribution of these lakes to the atmospheric methane budget is estimated.

OBJECTS AND RESEARCH METHODS

According to the phytogeographical zonality of western Siberia [22], there are three subzones—arctic, typical, and southern—in the tundra zone (Fig. 1). These subzones of western Siberia are located in the region of continuous permafrost.

Field experiments were carried out in August 2010 at two sites located in the tundra zone of the Yamal-Nenets Autonomous Okrug (Fig. 1): Yasavei (southern tundra) and Gyda (typical tundra). At these sites, during the observation period, the depth of soil thawing, on average, amounted to about 30 cm. Five lakes were studied at each site. These lakes are characteristic of northwestern Siberia: shallow (2–2.5 m in depth), floodplain, with flat and sometimes swampy shores. These lakes are small in area: from 10000 m^2 to 0.2 km^2 (Gyda site) and from 4000 m^2 to 1.8 km^2 (Yasavei site), with sandy–slimy bottoms.

Data obtained from field measurements of methane fluxes into the atmosphere from the surfaces of

Table 1. Basic territorial and climatic characteristics of the tundra subzones of western Siberia

Subzone type	T, °C			P, mm/year	$T_{>0}$, °C	Veg, day	S, 10^3 km^2	Q, % of area
	year	January	July					
Arctic tundra	−10.9	−24.8	5.1(August)	310	398	67	57.5	2.8
Typical tundra	−8.7	−24.3	9.8	288	827	96	110.0	5.8
Sothern tundra	−8.2	−24.2	10.9	330	935	100	176.0	3.9

Note: T is near-surface temperature, P is precipitation, $T_{>0}$ is the sum of positive temperatures, Veg is the length of period with a daily mean near-surface air temperature of no less than 5°C, S is area, and Q is the portion of lakes.

lakes located within the Tazovskii site (Fig. 1) are given in [23]. These measurements were taken in August 2009 on lakes with peaty bottoms; their depth was 2–3 m.

The fluxes of methane from lakes into the atmosphere were measured using the static-chamber method [24]. Plastic chambers 30 × 40 × 40 cm in size with a light-reflecting coating were used; these chambers were held on the water surface with the aid of floats. The exposure time (the time interval between the point when the chamber was placed on the water surface and the last gas sampling) was 24–30 min. During this period, four chamber-air samples were taken with an interval of 8–10 min. In this case, the first sample was taken at the instant a chamber is placed on the water surface. SFM three-component single-use plastic syringes 10 mL in volume were used as air samplers. After chamber-air sampling, the syringes were hermetically plugged and delivered to a laboratory, where a quantitative analysis of the gas was made. The concentration of methane in each of the syringes was analyzed using a Crystal-5000.1 chromatograph fitted with a flame-ionization detector with steel columns (3 m) filled with the HayeSepQ80/100 sorbate and nitrogen as a carrier gas. The fluxes of methane into the atmosphere from the surfaces of lakes were calculated using the method of linear regression with weights.

Methane is generated in lakes under anaerobic conditions as a result of the decomposition of organic matter in bottom sediments by microorganisms (methane of biogenic origin). Methane can arrive at the water mass of a lake from its underground disposals along cracks in the upper layers of the earth's crust (methane of abiogenic origin). We assume that some deposits of underground ice in the cryolite zone can contain a significant amount of methane that enters thermokarst lakes during their development. The methane generated in bottom sediments and arriving from the subsoil is partially absorbed by a number of lake microorganisms, and the rest of it is emitted into the atmosphere through molecular diffusion, bubble transport, and vascular plants growing in the shallow near-shore zones of lakes. It should be noted that the floating static chambers record mainly diffusive methane fluxes. The probability that these chambers will record bubble fluxes from the so-called point sources (strong and narrow bubble jets from the bottom of a lake) is sufficiently small, because these sources occupy a very small portion of the water-surface area of a basin [12, 25].

In order to estimate the living conditions of microorganisms that oxidize methane in the water mass of lakes, the near-surface air temperature was recorded and the hydrothermal characteristics of the upper (50-cm) layer of lake waters-electrical conductivity, acidity (pH), dissolved-oxygen concentration, and temperature were determined. Both acidity and electrical conductivity were measured with a portable pH-meter-conductometer (Hanna Instruments HI 98129, United States). The concentration of dissolved oxygen was determined with a portable SG-6 oximeter (Mettler Toledo, Switzerland). The water temperature was measured with DS 1921–1922 Thermochron iButtons (Dallas Semiconductor, United States).

RESULTS AND DISCUSSION

The basic climate characteristics of the tundra subzones in western Siberia were determined on the basis of the 1980–2005 data obtained at meteorological stations: the Popov station on Bely Island and Dikson (arctic tundra), Antipayupa and Marresalya (typical tundra), and Mys Kamennyi and Novyi Port (southern tundra) [26] (see Table 1). The subzones under consideration are characterized by negative yearly mean near-surface temperatures, an annual precipitation amount of about 300 mm, and the sum of positive temperatures varying from 398°C (arctic tundra) to 935°C (southern tundra).

During the measurement period, the mean near-surface air temperature was 8.8°C (Gyda site), 11.4°C (Yasavei site), and about 18°C (Tazovskii site) (see Table 2). The upper water-layer temperature in lakes was determined by the air temperature, and it varied insignificantly during the measurement period, on average, amounting to 8.5, 12, and 18°C for Gyda, Yasavei, and Tazovskii, respectively.

An analysis of the acidity of waters in the lakes under study showed that the pH values varied from 5.1 to 6.5 (southern tundra) and from 7.1 to 7.5 (typical tundra) (Table 2). It follows from these data that the acid-base conditions of the water were acidic in the

Table 2. Basic characteristics of the upper (50-cm) water layer in tundra lakes of western Siberia

Object under study	T, °C	T_{up}, °C	pH	Eh, μS/cm	O_2, mg/L	CH_4, $mgCH_4/(m^2\ h)$	
						x_{av}	σ
Gyda site							
Lake 1	10.0	8.4	7.5	27.7	9.1	0.53	0.38
Lake 2	10.2	8.5	7.3	29.1	8.9	0.24	0.06
Lake 3	8.3	8.1	7.2	30.2	–	0.37	0.29
Lake 4	8.5	8.6	7.4	34.9	8.7	0.50	0.05
Lake 5	7.0	8.8	7.1	23.6	8.6	0.33	0.51
Yasavei site							
Lake 1	13.8	12.8	5.9	6.7	7.7	0.54	0.42
Lake 2	14.0	12.9	5.8	15.1	7.8	0.55	0.26
Lake 3	13.0	13.3	6.4	13.9	8.4	0.28	0.20
Lake 4	8.1	10.9	6.3	19.7	8.2	0.27	0.19
Lake 5	7.9	10.2	6.5	17.4	8.3	0.52	0.43
Tazovskii site							
Lake 1	11.0	16.6	5.2	14.7	–	2.93	2.77
Lake 2	20.7	17.7	5.3	5.1	5.6	2.47	0.67
Lake 3	20.3	18.4	5.3	18.3	5.4	1.05	0.31
Lake 4	21.7	20.0	5.1	14.5	7.7	0.75	0.40
Lake 5	16.0	17.5	5.3	7.3	7.7	0.72	0.66
Lake 6	18.0	18.0	5.3	8.9	7.9	0.81	0.63

Note: T_{up} is temperature, pH is acidity, Eh is electrical conductivity, O_2 is the concentration of dissolved oxygen, CH_4 is the flux of methane into the atmosphere (x_{av} is the average value and σ is the standard deviation), and T is the near-surface air temperature.

lakes of southern tundra and neutral in the lakes of typical tundra. The electrical conductivity of the lake waters varied from 5 to 35 μS/cm. The low values of this parameter imply that the mineral composition of the water in these lakes is poor. According to measurement results, the oxygen concentration in the upper lake-water layer amounted to 5–9 mg/L; this implies that the surface lake-water layer is rich in oxygen.

The low values of both salinity and pH of the waters in the lakes under study suggest unfavorable conditions for the life of microorganisms oxidizing methane in the water masses of these lakes. It should be noted that, in [15], on the basis of experimental data, it was revealed that the intensity of oxidation of methane in the water masses of lakes in the southern-tundra ecosystems of western Siberia is very low and amounted to 0.08% of the intensity of its oxidation in the near-bottom layer and 0.05% of the intensity of its generation in bottom sediments.

An analysis of experimental data showed that, in different tundra subzones, for the lakes whose bottom sediments contain an insignificant amount of organic matter, the ranges of variations in the mean values of methane fluxes into the atmosphere coincide: 0.24–0.53 $mgCH_4/(m^2\ h)$ for Gyda and 0.27–0.55 $mgCH_4/(m^2\ h)$ for Yasavei (see Table 2). It should be noted that the values obtained for methane fluxes are close to an estimate of 0.2 $mgCH_4/(m^2\ h)$, which was revealed in [15] (for the similar fluxes from lakes with insignificant bottom reserves of organic matter in the southern tundra of western Siberia), and to the range of variations in the mean values of methane fluxes 0.13–0.4 $mgCH_4/(m^2\ h)$, which was determined in [16] for forest-tundra lakes in western Siberia. The lakes within the Tazovskii site had peaty bottoms rich in organic matter and, as a consequence, higher mean values of methane fluxes 0.72–2.93 $mgCH_4/(m^2\ h)$.

Table 3 gives the statistical characteristic of the distributions of methane fluxes from tundra lakes into the atmosphere for the sites under study. The medians of methane-flux distributions for the southern tundra exceed those for typical tundra, which is quite expected if climatic conditions in the regions under study are taken into account (see Table 1).

The results of observations showed that oxidizing bacteria in the Gyda lakes absorbed an insignificant amount of atmospheric methane (see Table 3). A significant increase in the flux of methane, which was noted in analyzing air samples from a chamber on the

Table 3. Statistical characteristics of the distributions of methane fluxes ($mgCH_4/(m^2\ h)$) into the atmosphere from tundra lakes in western Siberia

Characteristic	Typical tundra	Southern tundra	
	Gyda site[1] ($n = 40$)	Yasavei site[2] ($n = 40$)	Tazovskii site[3] ($n = 34$)
Minimum value	–0.03	0.00	0.02
Maximum value	1.55	1.53	7.59
Lower quartile	0.21	0.23	0.60
Median	0.35	0.37	1.14
Upper quartile	0.50	0.54	1.89
Average value	0.39	0.43	1.46
Standard deviation	0.32	0.33	1.40

Note: Positive fluxes imply the emission of methane into the atmosphere and negative fluxes imply its absorption; n is the number of measurement runs. Measurements were taken ([1]) on August 27 and 28, 2010, from 10:00 to 19:00; ([2]) on August 9–14, 2010, from 13:00 to 20:00; and ([3]) on August 22–25, 2009, from 10:00 to 20:00.

surface of one of the Tazovskii lakes, may suggest that the chamber captured a bubble methane flux from the bottom of this lake. In this case, it follows from the data obtained that the emission of methane from the surfaces of the lakes under study due to the bubble transport may exceed its emission due to a diffusion flux six times. The results of measurements of both bubble and diffusion fluxes of methane for tundra lakes in Alaska and northeastern Russia showed that the methane emission due to a bubble flux may exceed that due to molecular diffusion 1.5–27 times [12, 13, 27].

The probability density distributions of methane fluxes from the surfaces of the lakes within the experimental sites under study were plotted on the basis of measurement data and the method of histograms (Fig. 2). It follows from the dependences obtained that, for typical-tundra lakes, the most probable ranges of methane fluxes are 0.22–0.24 $mgCH_4/(m^2\ h)$ and 0.36–0.39 $mgCH_4/(m^2\ h)$. For southern-tundra lakes with insignificant organic matter in the bottom sediments, the methane fluxes range from 0.02 to 0.05 $mgCH_4/(m^2\ h)$ and from 0.37 to 0.43 $mgCH_4/(m^2\ h)$. The southern-tundra lakes, whose bottom sediments are rich in organic matter, are characterized by methane fluxes ranging from 0.07 to 0.12 $mgCH_4/(m^2\ h)$ and from 0.98 to 1.04 $mgCH_4/(m^2\ h)$.

The annual emission of methane from the surfaces of lakes is calculated on the basis of the experimentally measured specific flux of methane, the area of lakes, and the length of the period of emission. According to [24], the median value of the corresponding distribution was chosen as an estimate of the specific flux of methane from the lakes in each tundra subzone. This value was 0.35 $mgCH_4/(m^2\ h)$ for typical tundra and 0.56 $mgCH_4/(m^2\ h)$ for southern tundra. The fluxes of methane from arctic-tundra lakes were not measured. Taking into account the fact that the Gyda site (typical tundra) borders arctic tundra, we think that the estimate of methane flux for this site is characteristic also of arctic-tundra lakes.

The portions of lake areas were determined for each tundra subzone in western Siberia on the basis of a hydrological map of the ArcGIS software package (Table 1). According to this hydrological map, the lake area is slightly over 1.6×10^3 km^2 (arctic tundra), 6.4×10^3 km^2 (typical tundra), and 6.9×10^3 km^2 (southern tundra). Typical-tundra lakes with an area of over 10 km^2 occupy about 54% of the total lake area in this subzone. Large lakes occupy 47% of the total lake area in arctic tundra and 40% of the total lake area in southern tundra. The so-called intrabog small (in area) lakes, which enter the composition of the microlandscapes of boggy areas, are not shown in this hydrological map. In order to take into account these intrabog lakes, data presented in [28] on the relative areas of these water bodies in different types of bogs on

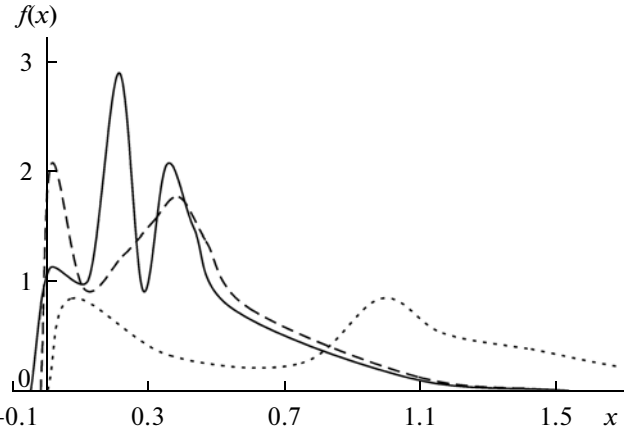


Fig. 2. Probability density $f(x)$ of the methane flux x ($mgCH_4/(m^2\ h)$) from lakes of typical tundra (solid line) and southern tundra (dashed line for the Yasavei site and dotted line for the Tazovskii site).

Table 4. Relative areas of different types of bogs and intrabog lakes for the tundra zone of western Siberia

Bog types according to [29]	Bog area (% of the tundra-subzone area)			Area of intrabog lakes (% of the bog area) according to [28]
	arctic tundra	typical tundra	southern tundra	
Type 1	21.2	9.6	8.0	0.0
Type 2	7.0	9.4	2.7	0.0
Type 3	0.2	0.5	5.4	17.7
Type 4	0.0	0.0	0.1	13.3
Type 5	0.0	0.0	0.7	0.2

Note: Polygonal-roller and polygonal-fissure bogs (Type1), polygonal bogs combined with grass- and moss-dominated bogs (Type 2), patterned (hollow and hollow-pool) flat-palsa bogs (Type 3), flat-palsa bogs combined with high-palsa bogs (Type 4), and shrub-dominated tussock bogs (Type 5).

the territory under consideration were used. In order to correctly use these data, on the basis of an electronic typological map of bogs in western Siberia compiled using the map presented in [29], the areas occupied by different tundra ecosystems in the region under study were determined, as were the areas of different tundra bogs (Table 4). The results of calculations showed that there are almost no intrabog lakes in the arctic tundra, while, in the southern tundra, such lakes occupy about 1% of the total area of this subzone.

According to data given in [13, 14], the flux of methane into the atmosphere from the open water surfaces of large lakes amounts, on average, to 11% of its emission from small lakes, and the shallow near-shore zone of large lakes occupies about 8% of their area. With consideration for these estimates, the portions of large lakes in the tundra subzones of western Siberia, and obtained experimental data, the daily emission of methane from the lakes of the region under consideration is estimated at 7.5 $mgCH_4/(m^2\ day)$.

Figure 3 gives the estimate of the flux of methane when compared to published data for tundra lakes in different regions. A wide range of measured values results from different measuring methods and natural conditions (different reserves of organic matter in the bottom sediments of lakes, weather conditions during measurements, etc.). The diffusion flux of methane from the water surfaces of tundra lakes in Alaska varies from 1.3 to 16.2 $mgCH_4/(m^2\ day)$, with an average of 6.9 ± 1.3 $mgCH_4/(m^2\ day)$ and a median of 8.3 $mgCH_4/(m^2\ day)$ [9]. According to experimental data on the emissions of methane from shallow plant-filled near-shore zones of small tundra lakes in Alaska, the estimate of the flux of methane from these lakes

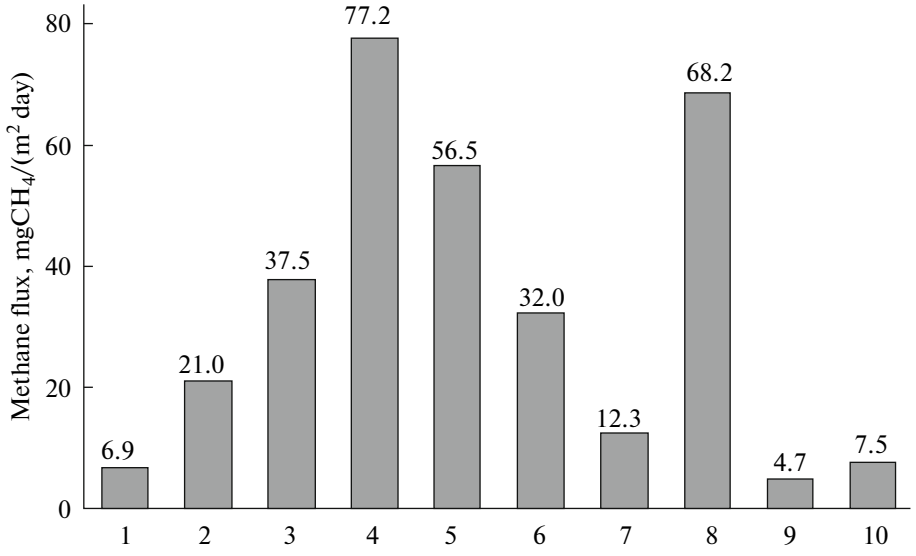


Fig. 3. Estimates of methane fluxes into the atmosphere from tundra lakes in Alaska (*1* according to [9], *2* according to [17], *3* according to [18], *4* according to [13], and *5* according to [19]), in northeastern European Russia (*7* according to [21] and *8* according to [12]), and in western Siberia (*9* according to [15] and *10* according to this work).

significantly increased up to 14.4–296.4 $mgCH_4/(m^2$ day) at an average flux of 37.5 ± 11.2 $mgCH_4/(m^2$ day) [18] and 77 ± 10 $mgCH_4/(m^2$ day) [13]. Using the improved method of taking into account the emission of methane through bubbles from thermokarst lakes increased the estimate of the flux of methane from these lakes into the atmosphere by more than five times from 12.3 ± 4.7 $mgCH_4/(m^2$ day) [21] to 68.2 ± 6.3 $mgCH_4/(m^2$ day) [12].

In this work, as well as in [23], the vegetation period, which is characteristic of the tundra subzone, i.e., the period with a daily mean near-surface air temperature of no less than 5°C, is taken as a period of methane emission in this subzone. According to meteorological data [26], the period of methane emission in the tundra zone of western Siberia lasts from 67 to 100 days (Table 1). In a number of publications, the period of methane emissions from tundra ecosystems was estimated from 100–106 days [20, 23, 30] to 120–130 days [12, 13]. According to the estimates, the methane emission from lakes in western Siberia over the warm season amounts to about 0.5 $KtCH_4$ (arctic tundra), 2.9 $KtCH_4$ (typical tundra), and 8.5 $KtCH_4$ (southern tundra). It should be noted that the indicated estimates of the emissions of methane from lakes are calculated on the basis of data obtained from field measurements taken on warm days in arctic summer (see Table 2). It follows from the results obtained in [31] that the monthly mean emissions of methane from northern lakes during the warm season (except for the ice-thawing period) vary insignificantly. Therefore, the calculation method used in this work must not yield a significant overestimation of the integral emission of methane over the warm period.

During the period of spring ice thawing, the methane icebound and accumulated under the ice during winter is emitted from lakes. The initial ice-thawing period (the first 10 days) is characterized by the largest amount of methane emitted from lakes [10, 31, 32]. In [10], the flux of methane into the atmosphere from small lakes in the middle latitudes of North America during ice thawing is estimated at 67% of the total methane flux from these lakes over the warm period. In [21], on the basis of the results of measurements and simulations of the fluxes of methane from the surfaces of thermokarst lakes in northeastern Russia, it was shown that no less than 75% of its annual emission from these lakes is contributed to by the methane generated under the ice cover. It should be noted that, in [21], calculations were performed on the basis of data obtained from studying lakes whose bottom sediments are rich in organic matter, because they consist mainly of thawed yedoma (Pleistocene-aged organic matter). It follows from experimental data given in [31] that, for northern-taiga lakes in Alaska, the flux of methane accumulated under the ice into the atmosphere amounts to about 68% of its flux over the warm period. The content of organic matter in the bottom sediments of tundra lakes in western Siberia is smaller than that in yedoma. Taking into account the results obtained in [10, 31], we assume that the emission of methane as ice thaws in tundra lakes in western Siberia amounts to 68% of its emission over the warm period. Under this condition, the short-term spring emission of methane from these lakes is estimated at 8.1 $KtCH_4$.

According to data given in [23], the emission of methane into the atmosphere from bogged areas in the tundra zone of western Siberia amounts to about 0.16 $MtCH_4$/year. On the basis of the calculations performed, the annual flux of methane from lakes in the tundra zone of western Siberia may be estimated at 20 $KtCH_4$. Thus, the emission of methane from lakes amounts to about 13% of its annual emission from the tundra zone of the region under consideration.

According to data given in [4, 8], the annual mean flux of methane from the total area of lakes into the atmosphere is estimated at 7.1 ± 4.9 $gCH_4/(m^2$ year). It follows from the obtained estimate of the annual flux of methane from tundra lakes in western Siberia that the intensity of the emission of methane from lakes in the region under consideration is estimated at 1.2 $gCH_4/(m^2$ year), which amounts to about 17% of the annual mean flux of methane from the unit of the area of the global lake network.

CONCLUSIONS

The lakes of the tundra ecosystems of western Siberia occupy about 17×10^3 km^2, which is 5% of the area of the region under consideration. The largest portion of these lakes (about 6%) is characteristic of the typical tundra of western Siberia. In both arctic and southern tundras, lakes occupy 3% and 5% of their areas, respectively. On the global scale, the area of tundra lakes in western Siberia is less than 0.4% of the total area of lakes.

The emission of methane from the surfaces of tundra lakes in western Siberia over the warm season is estimated on the basis of measured methane fluxes from these lakes. The amount of methane accumulated under the ice cover in the water bodies of the region under study is estimated with consideration for published estimates of the intensity of methane generation in northern-latitude lakes during the cold season. According to the results of calculations, the contribution of the tundra lakes of western Siberia to the atmospheric methane budget amounts to 20 $KtCH_4$/year, in which the portion of arctic-tundra lakes is 4%, the portion of typical-tundra lakes is 25%, and the portion of southern-tundra lakes is 71%. It should be noted that this estimate was obtained from measurements of mainly diffusive methane fluxes from the surfaces of these lakes. The emission of methane from tundra lakes through bubble transport may vary from 12% [13] to 95% [12] of its annual emission from these lakes. Therefore, the value of the intensity of the emission of methane from lakes into the atmosphere for the tundra zone of western Siberia should be

treated as a lower boundary of its emission from water bodies in this region. Taking into account the tendencies for variations in the rates of both productive and destructive processes in northern ecosystems [33, 34] and for the increase in the number of small-size thermokarst lakes in the continuous permafrost zone of western Siberia [35], one should expect an increase in the intensity of the emission of methane into the atmosphere from the region under consideration.

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