

Methane emissions from different ecosystem structures of the subarctic tundra in Western Siberia during midsummer and during the thawing period

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ABSTRACT

Methane emission was measured using a static chamber method at seven different ecosystem structures of the subarctic tundra on the Yamal Peninsula (West Siberian Lowlands, Russia) in August 1995 (midsummer) and June 1996 (spring thaw). The results obtained represent one of the most extensive data sets available for Siberian tundra and confirm the significance of this area as an important source of atmospheric methane. Mean midsummer emission rates ($4.24\text{--}195.3\text{ mg CH}_4\text{ m}^{-2}\text{ d}^{-1}$) were higher than mean rates reported for wetlands between $65\text{--}70^\circ\text{N}$ in Alaska, Sweden and Russia. The highest emission rates were measured in a lake terrestrialization mire which was always flooded, the lowest rates at a dry site in a polygonal mire. Mean emission rates during spring thaw ranged from 0.16 to $56.2\text{ mg CH}_4\text{ m}^{-2}\text{ d}^{-1}$. These rates increased at 4 out of 5 sites from $2.4\text{--}15.1\text{ mg CH}_4\text{ m}^{-2}\text{ d}^{-1}$ at the beginning of the measuring period to $24.2\text{--}156\text{ mg CH}_4\text{ m}^{-2}\text{ d}^{-1}$ at the end. The water-table level was the crucial parameter influencing spatial variation of methane emission rates, while temperature was the most important factor controlling temporal variation, especially during spring thaw. However, short-term changes of air temperature had no effect, and diurnal variation of methane emissions was never detected. In addition to the direct influence of temperature on methanogenesis, the indirect effect on soil thawing was apparent. Increasing thawing depth was positively correlated with methane emission. Rapid alterations of the water table also resulted in large episodic methane emissions. Methane emission exceeded the calculated methane production in spring, suggesting that accumulated methane from the previous year was also released. The results show that considerable methane emission occurs even in the spring without an active vegetation cover and without plant-mediated methane transport. This is a consequence of high methane production rates even at low temperatures, and of methane release via diffusion as the main transport pathway from the soil into the atmosphere.

1. Introduction

Natural wetlands are the largest source of atmospheric methane, an important greenhouse gas.

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Every year $100\text{--}200\text{ Tg}$ of CH_4 are released from these ecosystems into the atmosphere, accounting for more than 20% of global methane emission (IPCC, 1992; Cicerone and Oremland, 1988). About one-half of the global wetland area [$(5.3\text{--}5.7) \times 10^6\text{ km}^2$] is located in the region between 50°N and 70°N (Matthews, 1993). These high-latitude wetlands are characterized by accumulation of organic carbon in peat. Boreal, subarc-

tic and arctic wetland ecosystems contain about 455 Pg of organic carbon, or about 35% of the global terrestrial soil carbon pool (Gorham, 1991). Since the greatest greenhouse warming is predicted to occur in northern wetland regions, this vast organic carbon stock has a large potential for feedback effects on climate (Oechel and Vourlitis, 1994).

Most calculations of global methane emissions from northern wetlands are based on measurements made in Alaska, Canada and Sweden. However, more than 50% of the global area of boreal, subarctic and arctic wetlands is located in the former Soviet Union ($1.52 \times 10^6 \text{ km}^2$; Botch et al., 1995). In this region, where the largest uninterrupted wetland areas of the Earth, the Western Siberian Lowlands ($0.54 \times 10^6 \text{ km}^2$; Glooschenko et al., 1994) are located, few studies have been performed (Christensen et al., 1995; Panikov et al., 1993, 1995; Makov et al., 1994). Thus, this area is severely under-represented and there are a risk that the emissions from these regions are not properly estimated. The present work on methane emission from the subarctic treeless tundra region of northwestern Siberia is a step on the road to fill this gap in our knowledge.

The most important factors controlling temporal and spatial variations of methane emission in wetlands are soil temperature, water-table level, vegetation cover, topography and nutrient supply (Bartlett et al., 1992; Roulet et al., 1992; Morrissey and Livingston, 1992; Dise et al., 1993; Bubier et al., 1995; Frohling and Crill, 1994; Moosavi et al., 1996; Kettunen et al., 1996; Granberg et al., 1997; Chanton et al., 1995; Waddington and Roulet, 1996). In the permafrost region the hydrology, and thus the water-table level, is determined by topography. The plant community which develops is a consequence of average water-table height and nutrient supply, and can therefore be used as an indicator of the homogeneity of a studied area.

Calculated methane budgets for northern wetlands are based mainly on measurements taken during the growing season, which in the tundra is restricted to less than a third of the year. This focus on the growing season is based on the direct correlation between wetland plant cover and methane emission (Whiting and Chanton, 1993), due to the utilization of plant material as substrates for methane production (Chanton et al.,

1995). However, the observation that substantial methane emission from wetlands occurs during winter (Dise, 1992; Melloh and Crill, 1996; Nykänen et al., 1995; Alm et al., 1997; Whalen and Reeburgh, 1988) indicates that restricting measurements to the growing season underestimates annual emission rates.

The conditions for methane emission during winter are less favourable in permafrost soils than in temperate and boreal wetlands, where only the uppermost surface layer freezes. Treeless subarctic tundra is characterized by continuous permafrost, where the entire soil is frozen during winter and release of methane is unlikely. However, when the soil is only partially frozen in autumn methane production can continue and methane accumulates in the soil. Release of this methane during the spring thaw has been demonstrated by Friborg et al. (1997) and Windsor et al. (1992). From the beginning of thawing until the development of a vegetation cover there is no influence of plants on methane production and emission. Therefore, methane emission during this period should be controlled by different ecological factors than during the growing season.

The objectives of this study were to quantify methane emissions in different dominating ecosystem structures of the subarctic tundra, to determine the temporal and spatial variations of methane emission during summertime, to quantify methane emission during thawing of the permafrost soil and to assess the release of 'old' methane accumulated from the previous year, and to evaluate the relationship between ecological conditions and the spatial and temporal variability of methane emission.

2. Materials and methods

2.1. Study area

The measurements were conducted in the treeless subarctic tundra region of the Yamal Peninsula in northwest Siberia (Russia) from 6 to 29 August 1995, and during the thawing period from 7 to 27 June 1996. The study site is located in the south of Yamal ($68^{\circ}08'N$, $71^{\circ}42'E$), about 280 km northeast of the town of Salechard. Yamal is characterized by a very flat relief from sea, by river and lake terraces, permafrost soil and abundant ($> 50\,000$) small thermokarst lakes. Despite

the low precipitation (300–400 mm yr⁻¹), most soils have high humidity due to slow evaporation and slow surface runoff. The mean annual air temperature is -9.3 °C. Monthly means for June, July and August are 2.3, 10.2 and 9.8 °C, respectively. The mean number of days with a daily mean temperature >0 °C and >5 °C are 114 and 77, respectively.

The dominating wetlands are fens formed by terrestrialization of lakes or inundation near rivers and polygonal mires. Seven characteristic ecosystem structures were chosen for measurement. These differed with respect to plant community, water table, peat depth and thawing depth (Table 1).

2.2. Measurement of methane emission

Methane flux was determined using closed static chambers with manual sampling. Chambers (30 × 30 × 30 cm; volume 27 L) consisted of alumi-

nium frames fitted with Plexiglas panes and covers which could be opened and closed manually. The stainless steel frames were inserted 5 cm deep into the soil and fitted gas-tight to the chambers. Small battery-driven fans mixed the atmosphere inside the chambers before sampling. To avoid disturbance of the site during sampling, the gas samples were taken using a 10-mL syringe (Pressure-Lok, DYNATECH) at the end of a 3-m long steel tube (internal diameter 2 mm) connected to the chamber and closed by a septum. Sampled gas was injected through a septum into small tubes filled with saturated NaCl solution. Under these conditions storage and transport of the gas samples without changes in methane concentration were possible.

Two parallel chambers were installed at each ecosystem structure. The measuring chambers were put on the exact same spots in both years. Gas samples were taken at 0, 1, 2, 3, 4 h after chambers were closed. Thereafter the cover was

Table 1. Characteristics of the sites studied

Site	Dominating plant species	Water table (cm)	Peat depth (cm)	Thawing depth (cm)
A Lake terrestrialization mire	<i>Sphagnum</i> spec. <i>Comarum palustre</i> <i>Carex capitata</i>	+2 to -5	35	70
B Lake terrestrialization mire	<i>Polytrichum</i> spec. <i>Dicranum</i> spec. <i>Carex capitata</i> <i>Carex saxatilis</i>	+6 to +1	40	80
C River swamp mire	<i>Eriophorum vaginatum</i> <i>Polytrichum</i> spec. <i>Carex rariflora</i> <i>Salix</i> spec.	+4 to 0	25	70
D Lake terrestrialization mire	<i>Carex</i> spec. (tall species) <i>Eriophorum angustifol.</i> <i>Caltha arctica</i>	+10 to +5	>50	>100
E Lake terrestrialization mire	<i>Sphagnum</i> spec. <i>Polytrichum</i> spec. <i>Betula nana</i> <i>Salix</i> spec.	0 to -8	20	55
F Polygonal mire	<i>Ledum palustre</i> <i>Carex</i> spec. (short species) <i>Rubus chamaemorus</i>	-20	30	>100
G River swamp mire	<i>Eriophorum vaginatum</i> <i>Carex saxatilis</i>	+5 to 0	20	

+, Water table above the soil surface; -, water table below the soil surface.

opened for 2 h. Methane emission rates were calculated by linear regression of methane mixing ratios with time. The detection limit for the methane emission rates was $0.01 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$.

2.3. Methane analysis

Methane was analyzed using a gas chromatograph equipped with an FID (Perkin–Elmer GC-Autosystem: 1-m steel column, 1/8", CMS Typ G, 60/80 mesh; carrier gas N_2 , 60 mL min^{-1} ; H_2 , 40 mL min^{-1} ; synthetic air, 400 mL min^{-1} ; column temperature 100°C ; injector temperature 105°C ; detector temperature 225°C ; sample volume 1 mL). Methane in synthetic air (10 and 194 ppmv , Messer Griesheim) was used for calibration.

For the determination of methane concentrations in water, 5-mL water samples were injected into pre-evacuated BALCH tubes (16 mL) and the methane measured after equilibration with the headspace (Heyer and Suckow, 1985). The tubes were filled with 6 mL of saturated NaCl solution and 1.6 g of NaCl to inhibit microbial activity before analysis.

Methane concentration profiles in soil pore water were determined by a modification of the method of Hesslein (1976). A 32-cm long Plexiglas rod containing at 2-cm intervals two parallel, flat, 1.5-mL water-filled chambers which were closed by dialysis membranes (Union Carbide Corporation, Chicago) was fixed to a Plexiglas cover which had small holes over each chamber to allow dissolved gas exchange between interstitial soil water and the chamber water. The sampler was kept in the soil for 8–12 d. Thereafter, water samples from each chamber were analyzed for methane as described above.

2.4. Measurement of ecological parameters

Besides daily measurements of air temperature, air pressure and precipitation, the following parameters were determined at each site:

- temperature inside and outside the chambers during the emission measurements (hourly) using an Electronic Dual Thermometer with two channels;
- temperature profile in the soil (1-cm intervals) with an electronic thermometer equipped with a molybdenum resistance sensor at the tip of a

40-cm long steel tube (Ebro Electronic GmbH) (1995 two times; 1996 daily);

- water-table height (daily) inside an open glass-tube (with a swimming pointer) inserted into the peat soil;
- methane concentration profile in the soil (once per measuring period);
- methane concentration in the surface water (daily);
- air temperature 5 cm above the soil and soil temperature at 2, 5, and 10 cm depth at site C (automatically every 30 min; only 1996) with an HI 92804C portable K-type thermocouple data-logging thermometer with four channels for K-type thermocouple sensors at the tips of 12-cm long steel tubes (Hanna Instruments);
- thawing depth (daily; only 1996) with the steel tube of the electronic thermometer.

2.5. Determination of methane production

Rates of methane production were determined by laboratory incubations of peat sampled from different depths (0–5, 5–10 and 10–15 cm) in closed serum bottles (60 mL) in a nitrogen atmosphere. Samples of peat (20 g fresh weight) were placed into the serum bottles, which were capped with butyl rubber stoppers and crimped. The gas phase was removed by evacuation (3 min) and replaced by pure nitrogen gas 500 mbar above atmospheric pressure (repeated three times). Samples were incubated at different temperatures (5°C , 10°C , 15°C and 20°C) for 12 d, and methane mixing ratios in the headspaces of the bottles were analyzed at 0, 1, 2, 3, 5, 8 and 12 d.

3. Results

3.1. Ecological conditions

The mean air temperature outside the chambers during the methane emission measurements showed a considerable temporal variation of more than 20°C (Fig. 1, top panel; August 1995: 8.9 – 29.3°C , mean 18.5°C ; Fig. 2, top panel; June 1996: 0.4 – 20.9°C , mean 9.0°C).

Soil temperature profiles showed steep gradients. During the thawing period the temperature in each layer of the soil profile rose about 0.4°C d^{-1} . At the same time the thawing depth increased at all sites almost continuously by

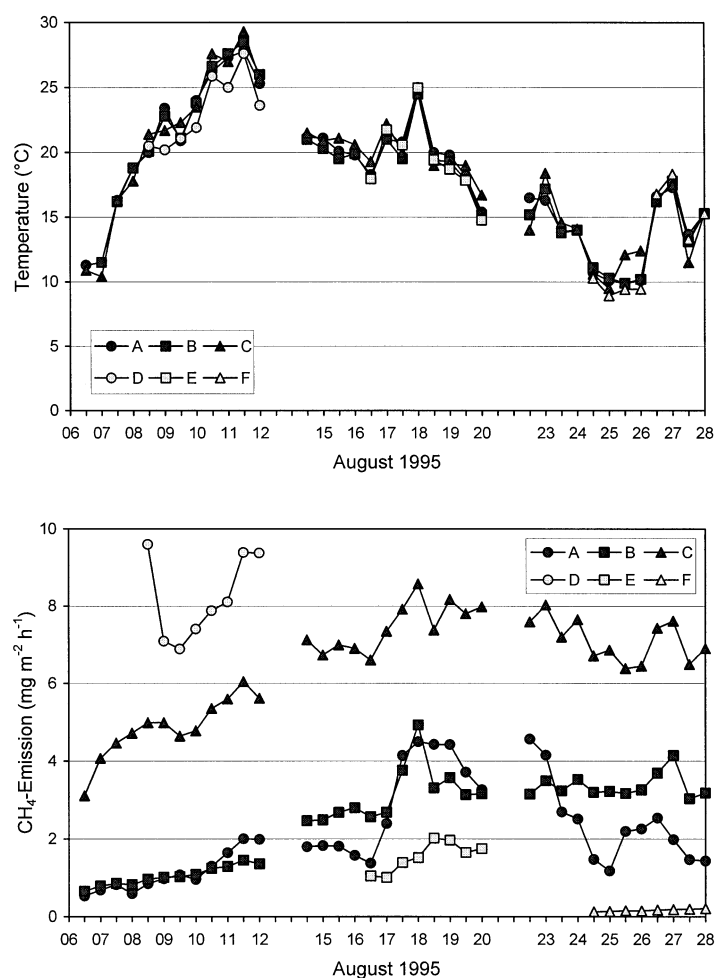


Fig. 1. Means of air temperature outside the chambers during the emission measurements in August 1995 at sites A-F (top panel) and temporal changes of methane emission at sites A-F (bottom panel, means of two parallel chambers).

1 cm d⁻¹, reaching a soil depth of 17–19 cm at the end of June (Fig. 3, bottom panel).

The temporal change of the water-table level was influenced by evaporation and precipitation during the summer 1995. A heavy rainfall event of approximately 50 mm in the night of August 17–18 caused a sudden rise in the water table by 5 cm at all sites. However, the variation of the water table during the whole observation period was less than ± 8 cm (Table 1). At the beginning of the thawing period in June 1996, changes of the water table at sites A and B were greater than in 1995 due to inundation of soils as a result of

snow and ice melting. With the run off of melt-water the water table decreased rapidly (Fig. 3, top panel).

3.2. Methane emission

The methane mixing ratios inside the chambers increased linearly during the closing time ($r^2 > 0.95$ in 98% of measurements) at low as well as high emission rates. Deviation from a linear increase, which can be caused, for example, by ebullition, was never observed.

The mean methane emission rates of ecosystem

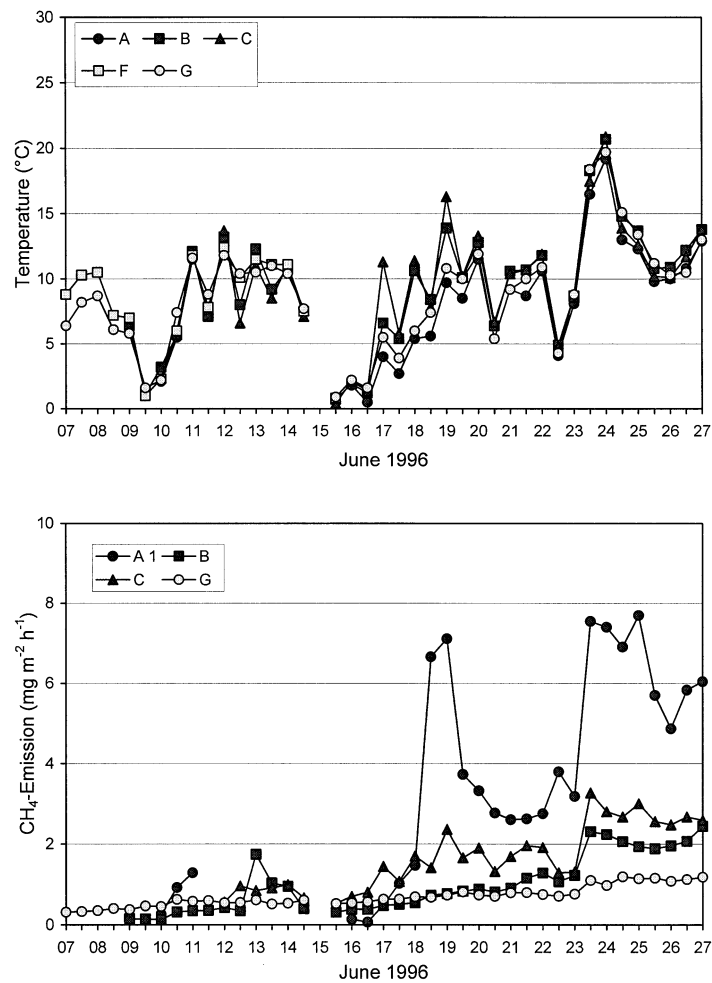


Fig. 2. Means of air temperature outside the chambers during the emission measurements in June 1996 at sites A–C, F, G (top panel) and temporal changes of methane emission at sites A–C, G (bottom panel; means of two parallel chambers except site A).

structures A–F in August of 1995 ranged from 0.18 to 8.14 mg CH₄ m⁻² h⁻¹ (Table 2; Fig. 1). The highest rates were measured at site D, which was covered with water during the entire measuring period. The lowest rates occurred at the dry site F, where the water table was at –20 cm. Uptake of atmospheric methane was never observed. The average emission rate calculated from all six ecosystem structures was 3.48 mg CH₄ m⁻² h⁻¹ = 83.5 mg CH₄ m⁻² d⁻¹ (4.2–195 mg CH₄ m⁻² d⁻¹).

Mean methane emission rates of five ecosystem structures (A–C, F and G) during the

thawing period in June 1996 (Table 2; Fig. 2) ranged from 0.01 to 2.34 mg CH₄ m⁻² h⁻¹ (0.16–56.24 mg m⁻² d⁻¹). The values at site A were higher in spring than in August 1995, despite the fact that the mean air temperature during the thawing period was about 10 °C lower.

Spatial differences in methane emissions are obvious from a comparison of mean emission rates at the seven different ecosystem structures across the two measuring periods (Table 2).

The methane emission during August 1995 varied at any particular site over less than one order of magnitude (Fig. 1). In June 1996 methane

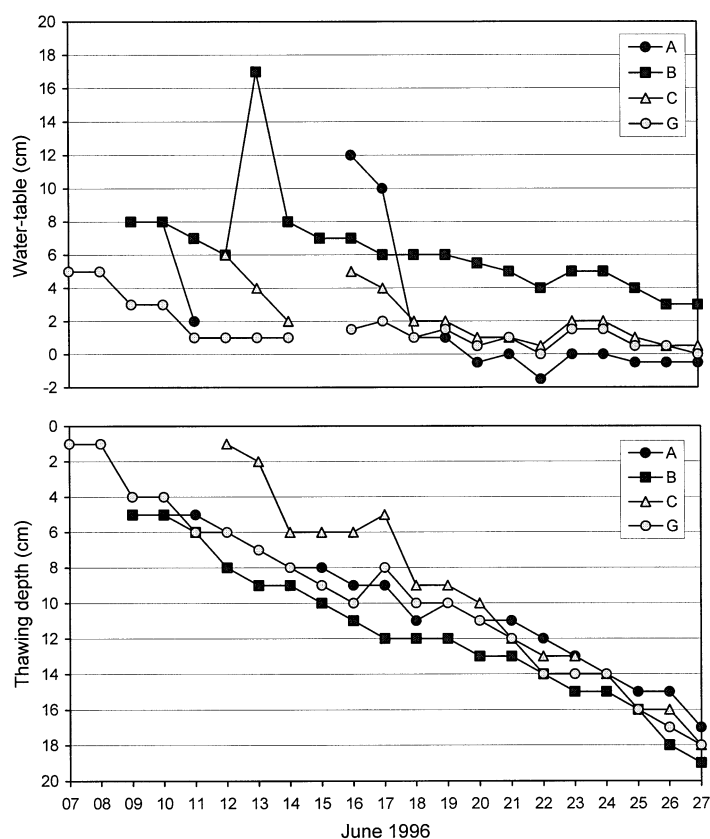


Fig. 3. Water table (top panel) and thawing depth (bottom panel) during the emission measurements in June 1996 at different sites A, B, C, G. The negative values of water table mean below the soil surface.

emission started on a low level and increased until the end of the measuring period (Fig. 2). In the final four days, mean emission rates at sites A, B, C and G were up to 25 times higher ($1.01\text{--}6.50\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$) than at the beginning of the measurements ($0.10\text{--}0.63\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$). Maximum emission rates at sites A, B, C, G were up to 70 times higher than minimum rates, demonstrating larger temporal variation than in the summer of 1995.

3.3. Methane production and methane concentration

Microbial methane formation in anoxic peat soil layers is the most important process for methane emission from the tundra ecosystem into the atmosphere. Methane production rates of three soil layers from sites A, B and C were determined

at different temperatures. The increase in methane concentrations during the incubation time was linear (data not shown). The highest methane production was observed in the 5–10 and 10–15 cm soil layers of all sites, while methanogenesis in the surface layer was very low (Fig. 4). At a temperature of 5°C more than $10\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$ was produced at all sites; at 15°C more than $20\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$.

The methane concentrations in the surface water of sites covered by water or having a water table close to the soil surface exhibited high spatial and temporal differences ranging between 0.1 and 185.4 (means: $1.4\text{--}75.5$) $\mu\text{mol L}^{-1}$ (Table 3).

The vertical profiles of methane distribution showed significant spatial differences during summer, with the highest methane concentrations at the inundated site D (Fig. 5) and with the lowest at site F. During the thawing period

Table 2. Mean values of methane emission rates in different ecosystem structures

Site	Chamber	Methane emission ($\text{mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$)					
		August 1995			June 1996		
		Mean	Range	<i>n</i>	Mean	Range	<i>n</i>
A	1	2.62	0.77–5.59	40	3.70	0.07–7.69	26
	2	1.57	0.30–3.70	40	0.99	0.09–3.37	26
Mean of site A		2.10			2.34		
B	3	2.63	0.73–5.09	40	0.99	0.09–2.59	36
	4	2.32	0.53–4.80	40	0.98	0.14–2.38	36
Mean of site B		2.48			0.99		
C	5	7.85	4.19–10.13	40	1.45	0.24–2.92	30
	6	5.03	2.03–7.03	40	1.88	0.63–3.63	30
Mean of site C		6.44			1.67		
D	7	8.34	2.99–10.30	10			
	8	7.93	6.40–8.94	10			
Mean of site D		8.14					
E	9	1.95	1.07–2.64	8			
	10	1.13	0.74–1.44	8			
Mean of site E		1.54					
F	11	0.13	0.10–0.15	10	0.01 ^{a)}	–0.03–0.06	17
	12	0.23	0.16–0.28	10	0.01 ^{a)}	–0.02–0.03	17
Mean of site F		0.18			0.01 ^{a)}		
G	13				0.67	0.34–1.09	40
	14				0.73	0.28–1.36	40
Mean of site G					0.70		

^{a)} Not significant.

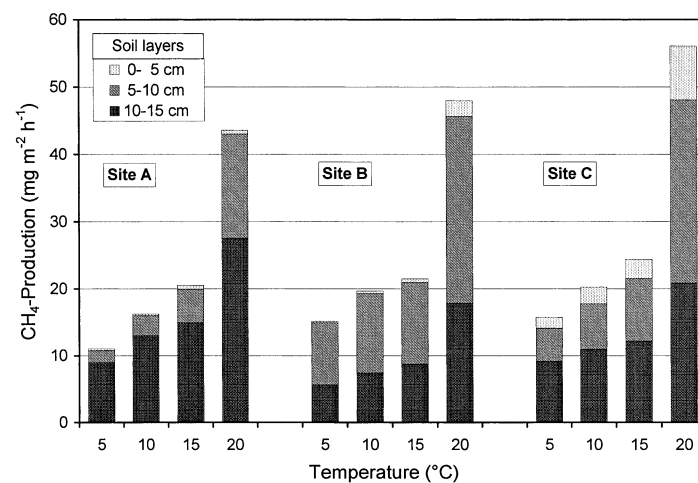


Fig. 4. Methane production rates in different soil layers and different temperatures at sites A, B and C (*in vitro* incubation of samples from June 1996).

Table 3. CH_4 concentrations in the surface water of sites A–D, G ($\mu\text{mol L}^{-1}$)

Sites	A	B	C	D	G
August 1995					
Mean	22.4	1.9	1.0	56.6	
Range	0.1–164.1	0.1–2.2	0.1–5.5	10.9–112.8	
June 1996					
Mean	75.5	2.8	4.3		1.4
Range	2.2–185.4	0.6–10.5	0.5–15.0		0.2–5.6

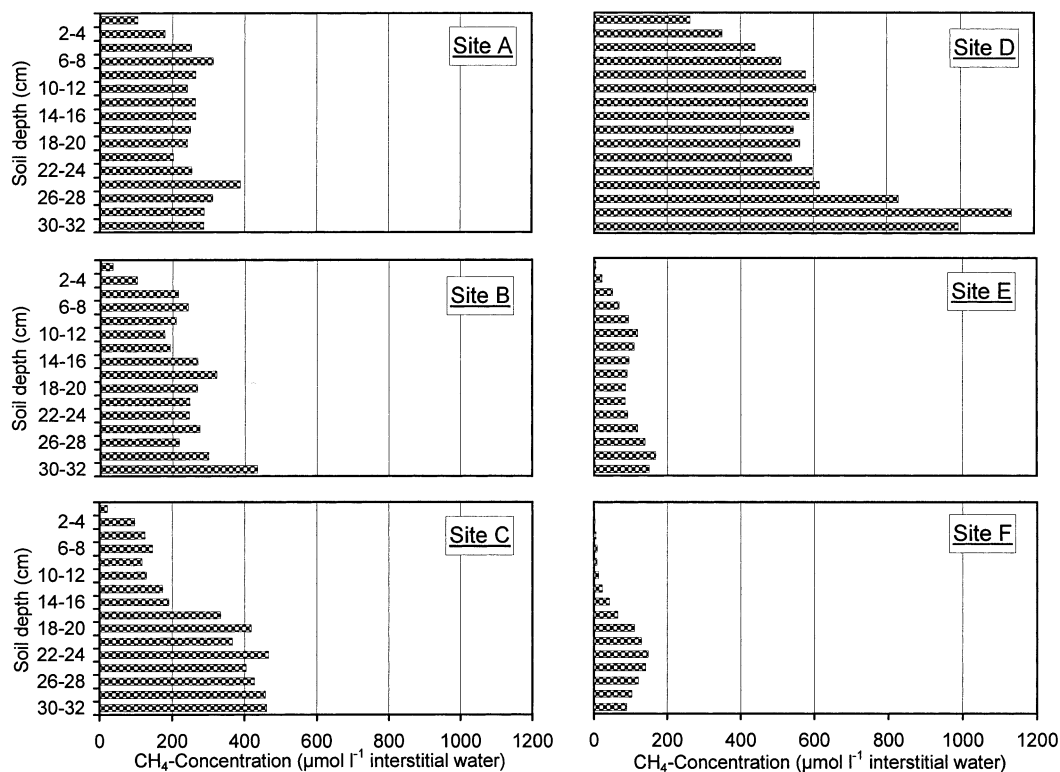


Fig. 5. Soil methane concentration profiles in August (10–22) 1995 at different sites (A–F).

the methane concentration profiles were more homogeneous (Fig. 6).

4. Discussion

4.1. Methane emission

Measurements of methane emission in seven different ecosystem structures of the subarctic tundra on the Yamal Peninsula resulted in the

most extensive data set for the Siberian tundra region (594 measurement series). These data confirm the significance of these ecosystems as an important source for atmospheric methane.

The average emission rate in August of 1995, calculated from all six ecosystem structures ($83.5 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$), was higher than mean methane emission rates reported for northern wetlands between the latitudes of $65\text{--}70^\circ\text{N}$ in Alaska (Sebach et al., 1986; Whalen and Reeburgh, 1988; 1990; 1992; King et al., 1989; Morrissey and

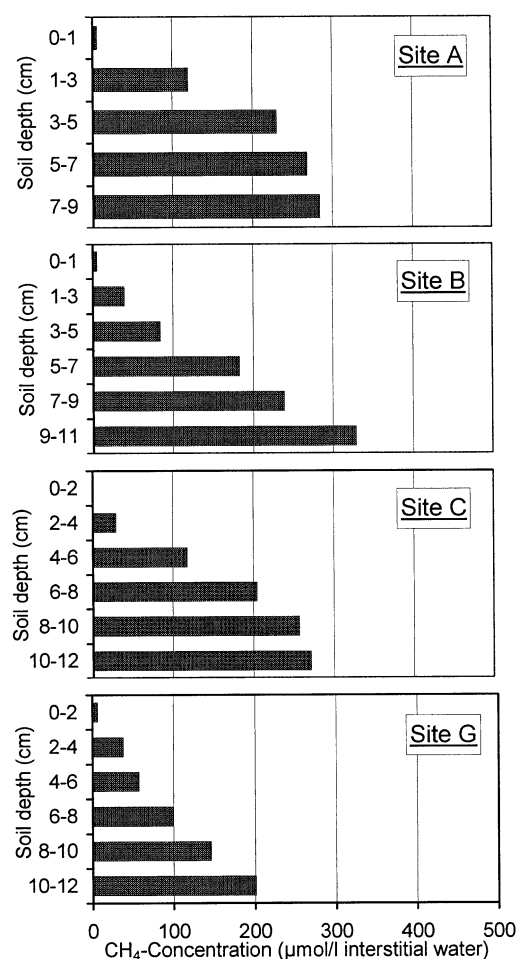


Fig. 6. Soil methane concentration profiles in June (20–29) 1996 at different sites (A–C, G).

Livingston, 1992; Christensen, 1993), Sweden (Svensson, 1976; Svensson and Rosswall, 1984) and Russia (Panikov et al., 1993; Christensen et al., 1995). The reasons for the high methane emission in Western Siberia could be the high water table, the relatively high pH value of the soil water (5.5–6.0) and a high degree of peat decomposition as a basis for methane formation.

The only previously published measurements from this region were conducted by Christensen et al. (1995). They found high emission rates in a palsa bog on the western coast of the Yamal Peninsula (70°N) of $105.5 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ in a wet depression and $1.4 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ in a

mesic elevation, but relatively low emissions (9.8 and $0.05 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$, respectively) from a polygonal bog on the north coast in the arctic tundra region (72°N).

4.2. Spatial variability of methane emission

Based on an analysis of variance, mean methane emission rates were significantly different in all ecosystem structures (except for sites A and B in summer 1995). Thus, the ecosystem structures represent suitable indicators for the estimation of spatial differences of methane emission and can be applied as basis for regional calculations in the future.

Regression analysis revealed a significant positive correlation between the mean water-table height and methane emission rate at all six sites in August 1995 (Fig. 7). Therefore, the spatial differences in methane emission of the ecosystem structures were probably due to differences in the water table. This conclusion agrees with findings in most other northern wetlands (Morrissey and Livingston, 1992; Bubier, 1995; Bubier et al., 1995; Granberg et al., 1997; Saarnio et al., 1997; Moosavi et al., 1996; Christensen et al., 1995). Only few studies indicate a weak correlation between methane emission and water-table height (Hutchinson et al., 1996; Frohking and Crill, 1994).

The water-table level determines the extent of the anoxic peat layer and therefore the intensity of methanogenesis per area. Furthermore, the mean water-table height has a crucial influence on the development of a characteristic plant community. The vegetation cover may in turn affect methane

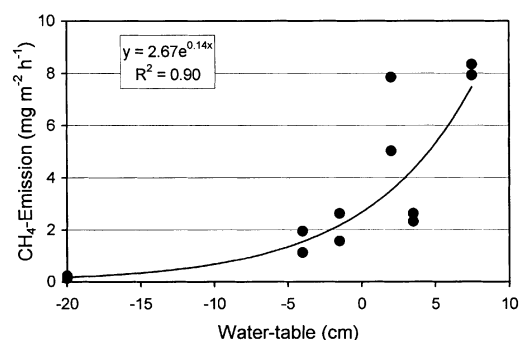


Fig. 7. Regression analysis between the means of water table and methane emission at six ecosystem structures (A, B, C, D, E, F) in August 1995.

emission by primary production and exudation of organic substances, and by transport of methane and oxygen between the anoxic soil and the atmosphere through the aerenchyma of plants. At sites with the lowest emissions and the lowest water tables (E, F) dwarf shrub communities had developed, whereas at sites with high water table and high methane emissions (D, C, A, B) the vegetation cover was dominated by *Carex* and *Eriophorum* species. These wetland plants have a high capability for gas transport between the soil and atmosphere.

The comparison of means of methane emission at the different sites (Table 2) with the methane concentration profiles in the soil (Figs. 5 and 6) demonstrates that the spatial differences of methane emission in several of the ecosystem structures were closely related to the methane concentration in the soil in both measuring periods (Table 4). Between the methane emission and the methane amounts in the upper soil layer (10 cm), calculated from the methane concentration profiles, a significant positive correlation was found.

4.3. Temporal variability of methane emission during summer

The temporal variability of methane emission was controlled mainly by temperature (Fig. 1). A

Table 4. Comparison of mean methane emission rates and the total amount of methane in the 0–10 cm soil layer at different sites, and results of a correlation analysis

Site	CH ₄ amount (mg m ⁻²)	CH ₄ emission (mg m ⁻² h ⁻¹)
August 1995		
A	321.2	2.10
B	232.0	2.48
C	146.1	6.44
D	618.8	8.14
E	68.4	1.54
F	7.3	0.18
June 1996		
A	302.6	2.34
B	205.9	0.99
C	175.9	1.67
G	100.4	0.70
Correlation CH ₄ emission/CH ₄ amount		
1995 + 1996		$r = 0.71$
August 1995		$r = 0.73$
June 1996		$r = 0.86$

significant positive correlation was found between methane emissions from 6–12 August and the temperature at each chamber at sites A, B and C (correlation coefficients $r = 0.78, 0.98, 0.95$). During the measurements between 15 and 29 August there was no such positive correlation and the temporal variation of methane emission must have been caused by other ecological factors. A weak correlation between methane emission and temperature has been observed elsewhere by Moore et al. (1994).

In order to indentify diurnal variation of methane emissions, additional measurements were conducted during two nights in August 1995 at five sites (A, B, C, D, F). Air temperature showed a characteristic diurnal pattern with day/night differences of up to 20 °C (11/12 August) and 10 °C (28/29 August), respectively. However, a diurnal variation of methane emission was not found in 16 measurements at the five ecosystem structures. The correlation between temperature and methane emission was not significant (correlation coefficients $r = -0.32-0.53$; significance threshold 0.62 for $p = 0.01$). From these results it is assumed that short-term changes of air temperature in August only influenced the upper soil layers, whereas soil temperatures remained nearly constant in the deeper peat layers. Therefore, the influence of short-term variations of air temperature on methanogenesis, mainly concentrated in the deeper peat layers, was low.

Because of the lack of diurnal variation of methane emission during the measuring period in August, other environmental factors that change diurnally, such as photosynthesis, release of substrates for methanogenesis, and transport of methane through plants (Mikkilä et al., 1995; Thomas et al., 1996; Chanton et al., 1993; Whiting and Chanton, 1996), also seem not to contribute to the variation of methane emission in the ecosystems studied here.

A sudden increase in methane emission was observed at all measuring chambers of sites A, B, C and E from 17 to 18 August (Fig. 1). This could not be explained by changes in temperature. During this time the water table rose considerably as a consequence of a strong rainfall. Accordingly, a significant positive correlation between methane emission and water-table height could be confirmed for this short measuring period (Fig. 8). We assume that this episodic increase in methane

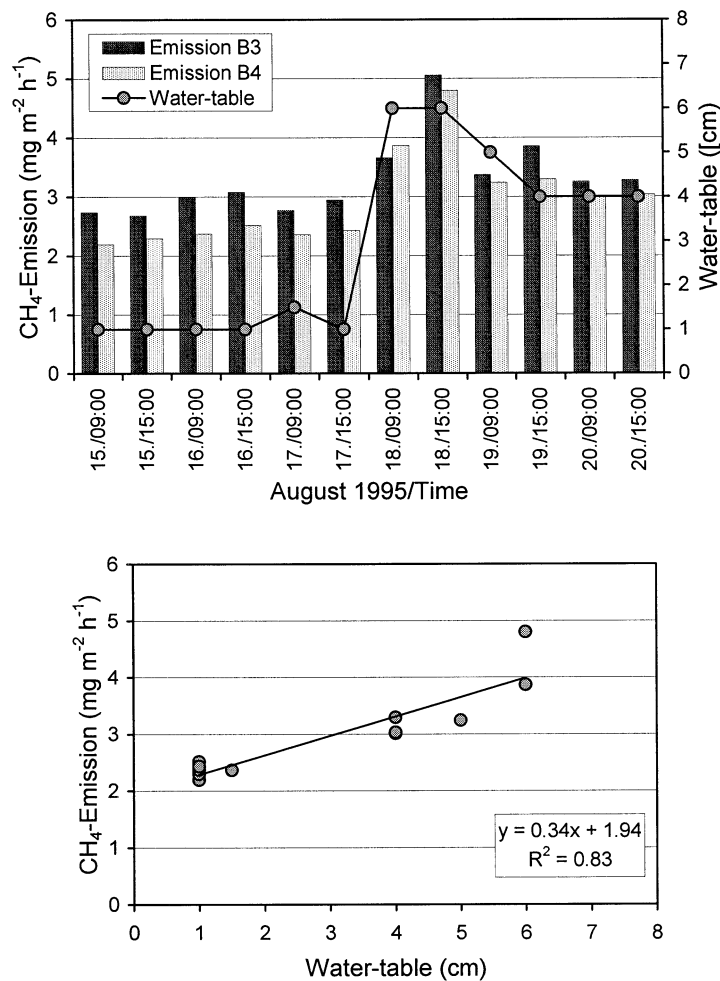


Fig. 8. Temporal variations of methane emission (parallel chambers B3 and B4) and water table at site B in August 1995 (top panel) and regression analysis (bottom panel).

emission resulted from an extension of the total anoxic soil layer and enhanced methane production. Mikkilä et al. (1995) found the same pattern of increase in methane emission after rainfall, and considered that an inhibition of methane oxidation was also possible. Frolking and Crill (1994), on the other hand, found a decrease in methane emission after rain and postulated an increase in hydrostatic pressure and the displacement of gas spaces in soil with water.

4.4. Methane emission during thawing period

During the thawing period there were fundamental differences in the ecological conditions

compared with the midsummer period, including: (a) the absence of an active vegetation cover; (b) a lack of root exudation of organic substances; (c) the absence of plant-mediated gas transport and therefore methane could be released solely by diffusion across the water–air boundary layer; (d) a lack of plant-mediated oxygen transport into the anoxic soil; (e) a low but increasing thawing depth of permafrost soil; (f) a greater fluctuations of the water table because of snowmelt and runoff; and (g) a low but steadily increasing soil temperature. Despite these different conditions, a considerable amount of methane was released from the uppermost soil layer into the atmosphere in four

of the five studied ecosystem structures. At sites C and G the measurements started immediately with the beginning of thawing at the soil surface. The methane emission rates of $0.50\text{--}0.63\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$ (site C, 12 June) and $0.29\text{--}0.34\text{ mg CH}_4\text{ m}^{-2}\text{ h}^{-1}$ (site G, 7 June 1996) on the first measuring day are likely due to a release of methane produced in the previous year and not to concurrent methane production, because the oxic surface layer and the low temperature mean that methanogenesis was unlikely to occur.

During thawing, temperature was the crucial factor controlling temporal variations of methane emission at sites A, B, C and G. The correlation

of temporal changes of daily means of methane emissions and soil temperatures at 2 and 5 cm depth at site C is shown in Fig. 9 as an example. This significant positive correlation was found at all sites studied during the thawing period, for air temperature or for soil temperatures at 2, 5 and 10 cm depth.

A significant positive correlation between methane emission and soil temperature has been previously demonstrated for different wetland ecosystems (Bartlett et al., 1992; Morrissey and Livingston, 1992; Frolking and Crill, 1994; Edwards et al., 1994; Moosavi et al., 1996; Saarnio et al., 1997) and experimental peat columns

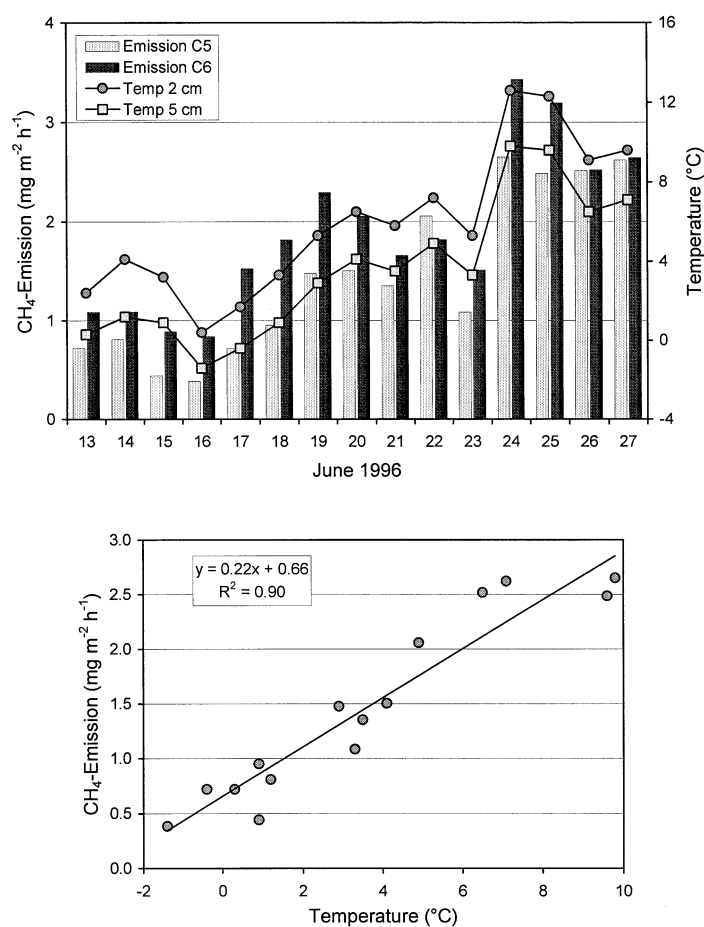


Fig. 9. Temporal changes of daily means of methane emissions (parallel chambers C5 and C6) and soil temperatures at 2 and 5 cm depth at site C in June 1996 (top panel) and regression analysis between methane emission (C5) and soil temperature at 5 cm soil depth (bottom panel).

(Thomas et al., 1996). The temperature effect results primarily from a direct influence on microbial methane production.

In spring the thawing depth of the permafrost soil is an important ecological factor influencing the temporal variations of methane emission. Emission measurements commenced when the thawing depth was 5 cm at the inundated sites A and B, and 0 cm at sites C and G. When measurements finished 15–20 d later the thawing depth was between 17 and 19 cm. For all chambers a significant positive correlation between the temporal changes of thawing depth and methane

emission could be demonstrated. An example is shown in Fig. 10.

Thawing of permafrost soil is controlled primarily by air temperature, solar radiation and by the ecosystem structure. We assume that, besides its direct influence on the process of methanogenesis, the indirect effect of temperature on thawing contributes to enhanced methane emission. A relation between methane emission and thawing depth has also been described by Vourlitis et al. (1993) for coastal tundra of North Alaska.

A sudden increase in methane emission during the thawing period (Fig. 2) at site A (18–19 June)

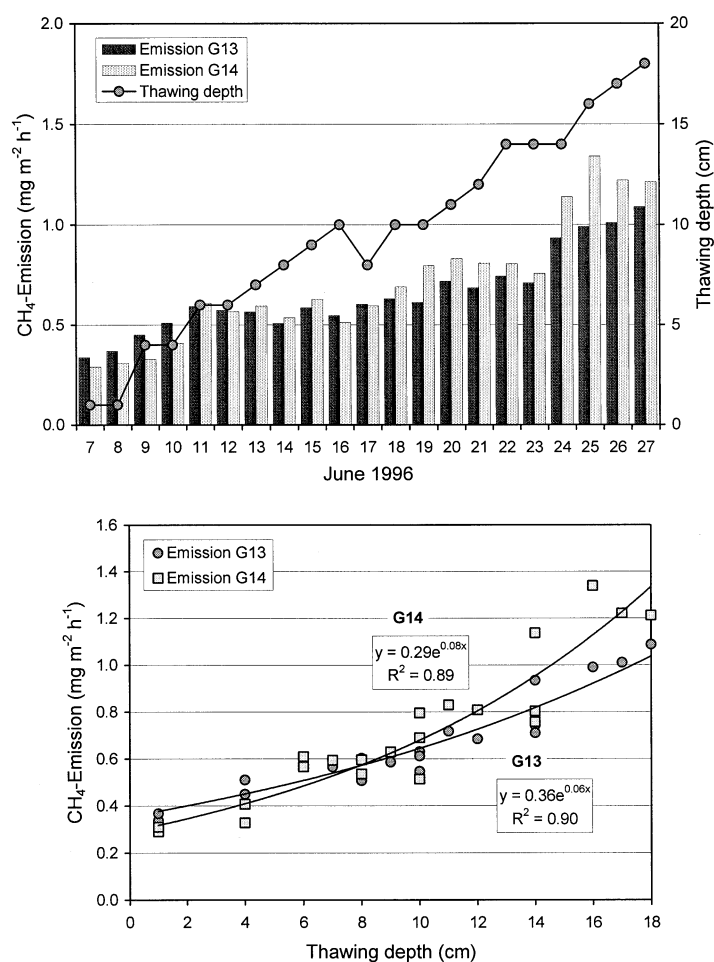


Fig. 10. Temporal changes of thawing depth and the daily means of methane emission at site G in June 1996 (parallel chambers G13 and G14; top panel) and regression analysis (bottom panel).

and site B (13–14 June) could not be explained by changes of temperature or thawing depth; however, these episodic events were related to a rapid drop of the water table (A, from 12 to 1 cm; B, from 17 to 8 cm) (Fig. 11). The enhanced methane release (3–5 times) was probably due to a reduction of the hydrostatic pressure as a consequence of the water-table drop at sites with high methane concentrations in the upper peat layers. This relationship between the water table and a short-term increase in methane emission agrees well with other findings (Moore et al., 1990; Windsor et al., 1992; Moore and Roulet, 1993).

At site A the increased methane emission was accompanied by a sudden increase of methane concentration in the surface water from 2.3 to 117.9 $\mu\text{mol L}^{-1}$ (Fig. 11). Furthermore, a significant positive correlation between the variations of methane emission and methane concentration was found in spring (correlation coefficient $r = 0.76$;

significance threshold 0.68 for $p = 0.01$). Because diffusion is the dominating transport process for methane release from the soil into the atmosphere during the thawing period, the intensity of methane emission is dependent on the methane concentration difference in the boundary between water and air. We assume that the sudden increase of methane concentration in the water and thus the increase of methane emission resulted from the drop of the water table.

4.5. Methane production

The methane formation rates in the 0–15 cm soil depth layer (5°C , 265–379; 10°C , 391–486; 15°C , 493–585; 20°C , 1046–1346 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) were in the same range as described for bogs in North Sweden (50–1700 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$; Sundh et al., 1994), the Hudson Bay Lowlands (43–3200 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$; Valentine et al., 1994), and different open bogs in North America (144–898 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$; Yavitt et al., 1997; 620 $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$; Moore and Dalva, 1997). An exact comparison is difficult due to differences in soil depth, temperatures and ecosystem type.

The high methane production rates at 5 and 10°C are ecologically important because August soil temperatures at 10 cm depth were lower than 10°C at all sites. Comparably high methane production activities have also been reported by Yavitt et al. (1997) for peat soil from Minnesota and New Hampshire at incubation temperatures of 2 and 12°C .

Peat soil samples were taken when there was no visible vegetation development, and therefore methane production was based on the decomposition of 'old' organic matter, accumulated products of decomposition formed before freezing.

The methane production rates determined in this study increased almost continuously in the temperature range 5 – 15°C , but more than doubled in the interval from 15 to 20°C . Accordingly, the Q_{10} -values for methanogenic activity depended on the temperature range used for calculation. The mean Q_{10} -values for the 0–15 cm deep soil layer of the three sites ranged at 5 – 15°C between 1.6 and 2.3, but at 10 – 20°C the values were between 3.0 and 3.4. This phenomenon may be explained by the presence of several populations of methanogenic bacteria with

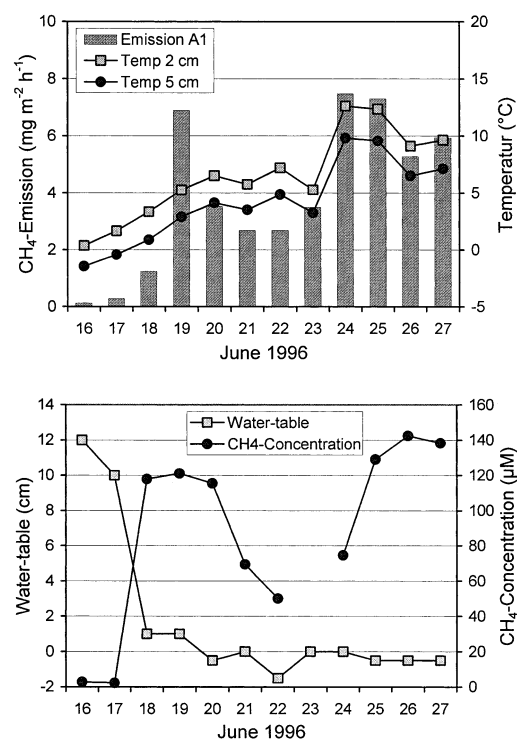


Fig. 11. Temporal variations of methane emission and soil temperature (top panel), and water table and methane concentration in the surface water (bottom panel) at site A in June 1996 (daily means).

different temperature optima; an acetotrophic population with a lower optimum and a hydrogenotrophic one with an optimum near 20 °C (Svensson, 1984; Kotsurbenko et al., 1993; Wagner and Pfeiffer, 1997). The Q_{10} -values calculated for the different layers of the three sites (1.3–5.6) agree with the results of Yavitt et al. (1997) (1.1–4.5) and Valentine et al. (1994) (1.7–4.7).

4.6. Balance of methane production and emission

For sites A, B and C, *in situ* methane production was calculated using the results of laboratory peat incubations, taking into account the actual temperatures measured daily at different depths of the thawing soil. The comparison of methane emission rates at site A with the calculated methane production rates showed (Fig. 12) that over the entire measuring period in spring only 62% of the total methane released could have resulted from concurrent methane production. The difference must be explained by the release of 'old' methane trapped in the frozen peat from the previous year. When a sudden increase of methane concentration and methane emission was measured on 19 June 1996, only 9% of the methane released into the atmosphere could be explained by concurrent methane production according to this calculation (Fig. 12). We assume that in the open tundra, where the permafrost soil reaches its maximum thawing depth of 50–100 cm, the upper soil layer freezes

rapidly over in autumn. As a result of the continuing methanogenesis in deeper soil layers, methane is accumulated under the ice cover. As the upper soil layer thaws in spring a considerable episodic methane release can be expected. The conditions for thawing and freezing of peat soil are different at different sites. Therefore, enrichment of methane is not possible at all sites. For example at site C the calculated methanogenesis significantly exceeded the methane emission (data not shown). In spite of these differences a significant positive correlation between methanogenesis and methane emission could be demonstrated for all three sites (A, $r = 0.74$, B, $r = 0.93$, C, $r = 0.91$).

The best conditions for continued methanogenesis after surface freezing are found in open water lags and in shallow tundra lakes, which have the deepest and longest permafrost thawing. Accordingly, Semiletov et al. (1996) and Zimov et al. (1997) demonstrated a considerable methane release in winter through ice holes of northeastern Siberian tundra lakes, and Smith and Lewis (1992) found high spring methane emissions in four mountain lakes. Enhanced methane emission during spring thaw by the sudden release of accumulated methane has also been observed by Windsor et al. (1992) for two subarctic bogs in Quebec, by Bubier et al. (1995) in open water lags of graminoid bogs in Manitoba, both using chamber measurements, and by Friborg et al. (1997) in a subarctic tree-less bog in North Sweden (Stordalen mire) using micro-meteorological methods.

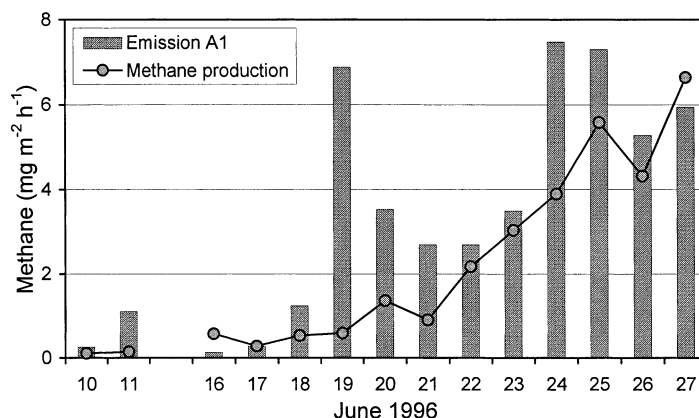


Fig. 12. Comparison of measured methane emission and calculated methane production at site A in June 1996 (daily means).

5. Conclusions

(1) The data of the present study demonstrate that wetlands of the subarctic tundra in Western Siberia are an important source for atmospheric methane. (2) The characteristic ecosystem structures in this region differed significantly in mean methane emission rates and thus represent suitable indicators for the estimation of spatial differences of methane emission as basis for regional calculations in future. (3) The height of the water table is the most important factor controlling spatial differences of methane emission. (4) The temperature is the crucial controlling factor of temporal variations of methane emission. (5) Sudden changes of water-table height result in episodic changes of methane emission. (6) In the spring thawing period a significant methane emission from the tundra wetlands into the atmosphere takes place because of the release of 'old' methane

from the previous year and high methane production rates at low temperatures. (7) Methane emission during this period occurs mainly by diffusion and without direct influence of an active vegetation.

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