Methane Emission from Siberian Wet Polygonal Tundra on Multiple Spatial Scales: Vertical Flux Measurements by Closed Chambers and Eddy Covariance, Samoylov Island, Lena River Delta

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Abstract

Ecosystem-scale measurements and investigations of the small-scale variability of methane emission were carried out in northern Siberian wet polygonal tundra using the eddy covariance technique during the entire 2006 growing season. Simultaneous closed chamber flux measurements were conducted daily at 15 plots in four differently developed polygon centers and a polygon rim from July–September 2006. Our study site was located in the southern part of the Lena River Delta, characterized by arctic continental climate and comparatively cold, continuous permafrost. Controls on methane emission were identified by applying multi-linear and multi-nonlinear regression models. We found a relatively low growing season average methane flux of 18.7 ± 10.2 mg m^{-2} d^{-1} on the ecosystem scale and identified near-surface turbulence, soil temperature, and atmospheric pressure as the main controls on the growing season variation methane emissions. On the micro-site scale, fluxes showed large spatial variability and were best described by soil surface temperature.

Keywords: closed chambers; eddy covariance; flux; methane; Siberia; tundra.

Introduction

Introduction

Arctic tundra ecosystems cover an area of about 7.34 x 10^{12} m^2 (Reeburgh et al. 1998) and are underlain by permafrost. Despite increased research, especially in connection with the much stated concern of potential increased emission of climate-relevant trace gases from warming or thawing tundra areas, these sensitive high-latitude ecosystems with their complex network of interconnected processes and controls are far from being understood. Vegetation, state of the permafrost, soil texture, hydrology, and many other relevant parameters and consequently also processes controlled by these parameters vary greatly on small spatial scales. This is especially valid for methane emission on various scales from arctic wetlands (Christensen et al. 2000, Kutzbach et al. 2004, Whalen & Reeburgh 1992).

To our knowledge, only four studies reported methane flux data from Arctic tundra on the ecosystem scale using eddy covariance techniques, namely Fan et al. (1992) from western Alaska, Harazono et al. (2006) from northern Alaska, Friborg et al. (2000) from Greenland, and Hargreaves et al. (2001) from Finland. Manuscripts by Wille et al. (2008) and Sachs et al. (2008) reporting data from the Lena River Delta, Siberia, are currently in press.

On the other hand, many studies are available reporting point data using closed chamber methods (Christensen et al. 2000, Kutzbach et al. 2004, Whalen & Reeburgh 1992). While closed chamber methods have multiple inherent problems, such as the exclusion of atmospheric parameters and induced alteration of concentration gradients underneath the chamber, resulting in disturbed fluxes, they are widely used to investigate the small scale variability of methane fluxes. The eddy covariance method does not allow for a spatial resolution high enough to investigate that kind of variability in heterogeneous areas.

We conducted intensive field studies on the ecosystem (1 ha to 1 km^2) and micro-site scales (0.1–100 m^2) using eddy covariance and closed chamber methods simultaneously in order to investigate the temporal and spatial variability of methane emissions. For the first time, methane flux measurements on the ecosystem scale in Arctic Siberian tundra were carried out during an entire growing season from the beginning of June–September 2006, and measurements on the micro-site scale were conducted within the eddy covariance footprint from July–September 2006.

Material and Methods

Study site

The study site was located on Samoylov Island, 120 km south of the Arctic Ocean in the southern central Lena River

Delta (72°22′N, 126°30′E) and is considered representative of the active delta landscape. Over the past ten years, Samoylov Island has been the focus of a wide range of studies on surface-atmosphere gas and energy exchange, soil science, hydrobiology, microbiology, cryogenesis, and geomorphology (Boike et al. 2003, Kutzbach et al. 2004, 2007, Liebner & Wagner 2007, Schwamborn et al. 2002, Wille et al. 2008, Sachs et al. 2008).

Samoylov Island covers an area of about 7.5 km². The western part of the island (3.4 km²) is a modern floodplain with elevations from 1–5 meters above sea level (a.s.l.). The study site is located in the center of the Late-Holocene eastern part (4.1 km²) with elevations from 10–16 meters a.s.l. The surface of the terrace is characterized by wet polygonal tundra with a flat but regular micro-relief caused by the development of low-center ice wedge polygons. The typical elevation difference between depressed polygon centers and elevated polygon rims is up to 0.5 m (Kutzbach 2006). The poorly drained and hence mostly inundated centers are characterized by *Typic Historthels*, while *Glacic* or *Typic Aquiturbels* dominate at the dryer but still moist polygon rims (Soil Survey Staff 1998, Kutzbach et al. 2004). As the summer progresses, these soils typically thaw to a depth of 30–50 cm.

Hydrophytic sedges, as well as mosses, dominate the vegetation in the wet polygon centers (Kutzbach et al. 2004). Polygon rims are dominated by mesophytic dwarf shrubs, forbs, and mosses. Surface classification of aerial photographs taken in 2003 shows that elevated and dryer polygon rims cover approximately 60% of the area surrounding the study site, while depressed and wet polygon centers and troughs cover 40% of the area (G. Grosse pers. comm.. 2005).

The climate in the region is arctic continental climate characterized by very low temperatures and precipitation. Mean annual air temperature at the meteorological station on Samoylov Island was -14.7°C and mean precipitation was 137 mm, ranging from 72–208 mm in a period from 1999–2005 (Boike et al. 2008). Snowmelt and river break-up typically start in the first half of June, and the growing season lasts from mid-June through mid-September. The continuous permafrost in the delta reaches depths of 500–600 m (Grigoriev 1960) and is characterized by very low temperatures between -13°C and -11°C (Kotlyakov & Khromova 2002).

Ecosystem scale flux measurements

In situ ecosystem scale methane fluxes were measured using the eddy covariance (EC) method with a tunable diode laser spectrometer (TGA 100, Campbell Scientific Ltd., USA) for CH_4 analysis. A more detailed description of the technical set-up can be found in Sachs et al. (2008).

The EC system was set up in the center of the eastern part of Samoylov Island and was surrounded by a relatively homogenous fetch of wet polygonal tundra. Larger lakes were located at the periphery of a 600 m radius around the tower. Successful measurements were conducted for 103 days from June 9–September 19, 2006, covering an entire growing season (Sachs et al. 2008).

Additional parameters measured at the eddy covariance system and an automated long-term monitoring station 700 m south of the EC tower include air temperature, relative humidity, incoming and outgoing solar and infrared radiation, photosynthetically active radiation (PAR), barometric pressure, precipitation, and soil temperature data at various depths. Additional daily manual measurements at five sites in close proximity to the tower included thaw depth using a steel probe, soil temperatures in 5 cm depth intervals, water level, and soil moisture using a Theta Probe type ML2x (Delta-T Devices Ltd., Cambridge, UK) where no standing water was present.

The area from which 80% of the cumulative methane flux originated was calculated using a footprint analysis according to Schuepp et al. (1990). The upwind distance of this flux contribution was on average 518 m, the maximum contribution originated from an average distance of 116 m.

Small scale flux measurements

For small-scale flux measurements, five different micro-sites characteristic of the prevalent surface and vegetation features within the eddy covariance fetch were established in close proximity to the flux tower (Fig. 1).

Polygon 1 was a low-center polygon with standing water in the center. The northern side of the polygon rim showed signs of beginning degradation, which might serve as a hydraulic connection to surrounding polygon troughs. Vegetation in the center is dominated by *Drepanocladus revolvens* (100% coverage) and *Carex chordorrhiza* (8% coverage).

Polygon 2 was a high-center polygon with no standing water in the center due to drainage into surrounding thermokarst cracks and troughs. The vegetation was dominated by *Hylocomium splendens* (85% coverage) and *Tomentypnum nitens* (10% coverage).

Polygon 3 was a low-center polygon with a massive rim on the western side and a completely degraded rim on the eastern side, where a large thermokarst crack of more than 2

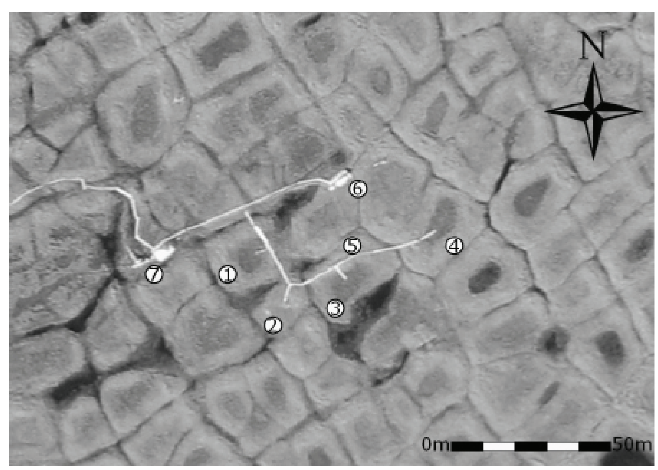

Figure 1. Aerial view of investigation site: 1 – low-center polygon, 2 – high-center polygon, 3 – low-center polygon, 4 – low-center polygon, 5 – rim, 6 – eddy covariance system, 7 – tent for equipment (Photo: J. Boike).

m depth was located. There was standing water in the polygon center and the vegetation was dominated by *Drepanocladus revolvens* (90% coverage), *Carex chordorrhiza* (10% coverage), and *Carex concolor* (10% coverage).

Polygon 4 was a low-center polygon with no apparent rim degradation and no apparent hydraulic connection to surrounding cracks or troughs. It usually maintained the highest water level and was dominated by *Scorpidium scorpidioides* (100% coverage), *Carex chordorrhiza* (8% coverage), and *Carex concolor* (3% coverage).

The polygon rim micro-site was underlain by a massive ice wedge and draining into polygon 3 to the east and the polygon crack to the west. Vegetation was dominated by *Hylocomium splendens* (60% coverage), *Rhytidium rugosum* (30% coverage), and *Carex concolor* (4% coverage).

In each of the four polygon centers and along the rim, three 50 cm x 50 cm PVC chamber collars with a water-filled channel as a seal were inserted 10–15 cm into the active layer. Chambers were made of opaque PVC and clear PVC, respectively, for light and dark measurements. Chamber volume was 12.5 l at the high-center and rim micro-sites and 37.5 l at the other sites, where higher vegetation did not allow for the use of small chambers.

Chamber measurements at all 15 plots were made daily from July 12–September 19, 2006 with both clear and opaque chambers. Sample air was drawn from a port on top of the chamber every 45 s for 8–10 minutes for simultaneous analysis of CO_2, CH_4, and water vapor using a photo-acoustic infrared gas spectrometer Innova 1412 with optical filters UA0982 for CO_2, UA0969 for CH_4, and SB0527 for water vapor (INNOVA AirTech Instruments, Denmark). A membrane pump was connected to two other ports and circulated chamber headspace air through perforated dispersive tubes for mixing.

Due to water interference with the CH_4 optical filter sample air was dried prior to entering the analyzer using 0.3 nm molecular sieve (beads, with moisture indicator; Merck KGaA, Darmstadt, Germany). Temperature and pressure inside the chamber were logged continuously by a MinidanTemp 0.1° temperature logger (Esys GmbH, Berlin, Germany) and the Innova 1412, respectively.

Flux modeling

We used multiple linear regression, as well as regression tree analysis, to identify the main controls on eddy covariance methane fluxes. All analyses were based on daily averages of measured and quality-controlled fluxes and are reported elsewhere in detail (Sachs et al. 2008). A multiplicative exponential regression model modified and extended after Friborg et al. (2000), was set up and fitted to the in situ data for small-scale flux modeling. It can be written as

$$FCH_4 = a \cdot b^{((T-\bar{T})/10)} \cdot c^{(u*-\overline{u*})} \cdot d^{(p-\bar{p})} \quad (1)$$

where a, b, c, and d are fitted parameters, T is the soil temperature at 10 cm depth in a polygon center, u_* is the friction velocity, p is the air pressure, and horizontal bars denote the mean values of the respective variables. A weighting factor of σFCH_4^{-2} was applied during the fitting process, with σFCH_4 being the daily mean of the noise estimates of the hourly flux data points.

For closed chamber measurements, we used multiple linear regression analyses to identify statistically significant controls on methane flux. Data was first tested for multi-collinearity following Schuchard-Ficher (1982) and for parameter significance using a t-test. The regressors were discarded in a stepwise procedure until only independent and significant parameters remained.

Results

Ecosystem-scale methane flux

Mean daily ecosystem methane flux was 18.7 ± 10.17 mg m^{-2} d^{-1} during the study period and showed relatively small seasonal variation (Fig. 2). However, strong variations could be observed, which coincided with pronounced decreases in air pressure and higher wind speed after calm periods.

In the first two weeks of measurements, average daily methane fluxes were already 13.8 mg m^{-2} d^{-1}, with high variability from 5.7 mg m^{-2} d^{-1} to 22.0 mg m^{-2} d^{-1}. Soil temperature was still below 0 °C when measurements started and showed very little variation in the early part of the thawing period. The lowest methane flux was observed during days with relatively high air pressure and low wind speed. Methane fluxes increased to an average of 25.0 mg m^{-2} d^{-1} in the third week. However, this increase was mainly due to an extreme peak on June 27, which coincided with the lowest observed air pressure during the summer and high wind speeds. The last ice from the bottom of ponds and smaller lakes surfaced and melted around this time.

Methane fluxes dropped to an average of 12.3 mg m^{-2} d^{-1} during the calm period at the end of June, and then steadily increased to the highest measured fluxes of on average 35.1 mg m^{-2} d^{-1} in the first week of August, roughly following variations in soil temperature and closely following variations in wind speed. Throughout July, above-average methane fluxes frequently correlated with rapid decreases in air pressure. Until the third week of August, fluxes remained between 17.0 and 20.0 mg m^{-2} d^{-1} and then decreased to less than 13.0 mg m^{-2} d^{-1} during a longer calm high-pressure period at the end of August.

During the first and second week of September, which were characterized by steadily decreasing air pressure, partly strong winds, and rain or snow events, methane fluxes increased to an average of 18.2 mg m^{-2} d^{-1} and 21.6 mg m^{-2} d^{-1}, respectively, despite a decrease in soil temperature and refreezing of the top soil layers and water bodies. By mid-September, all water bodies, except for the large thermokarst lakes, were covered with ice up to 8 cm thick. During the calm high-pressure period after September 13, methane fluxes decreased markedly to below 10.0 mg m^{-2} d^{-1} at the end of the measurement period.

All approaches showed that variation in methane fluxes could best be explained by friction velocity u_* and soil

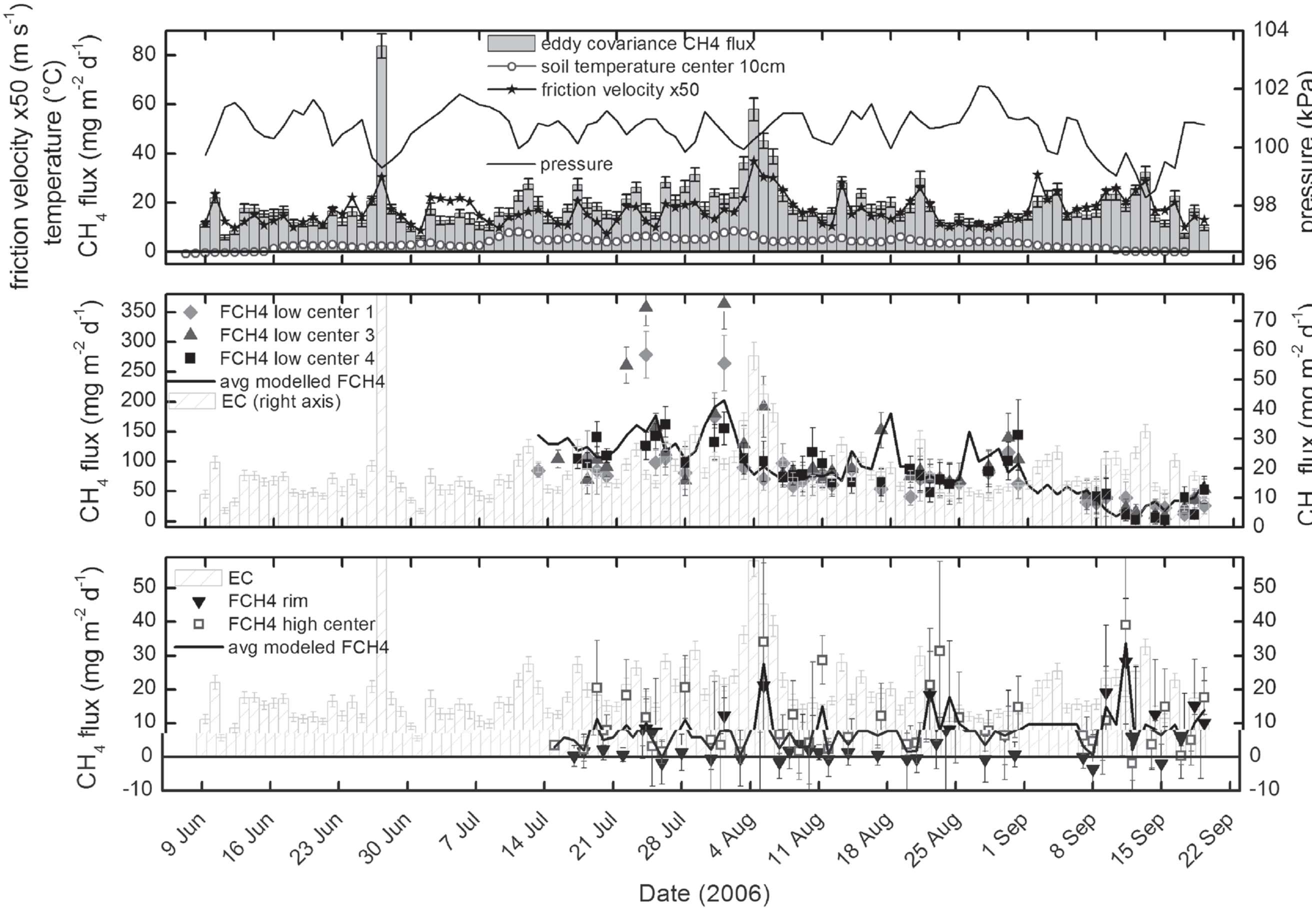

Figure 2. Top panel: Daily averages of eddy covariance methane fluxes and environmental controls during the 2006 growing season. The error bars of the eddy covariance data indicate the daily average noise level. Middle panel: Closed chamber methane fluxes from low center polygons and average modeled chamber flux. Each point represents the average of six flux measurements in the respective polygon. Bottom panel: Closed chamber methane fluxes from a polygon rim and a high center polygon and average modeled chamber flux. Each point represents the average of six flux measurements at the respective site. The error bars of the chamber data indicate the mean standard errors of the flux estimates. In the middle and bottom panel, the eddy covariance fluxes are given as light-grey columns for comparison. Note the different scale of the two y-axes in the middle panel!

temperatures at 10 cm depth in a polygon center and 20 cm depth in a polygon rim, respectively. Friction velocity alone accounted for 57% of the variance in methane emissions and another 3% could be explained by wind speed, which is closely correlated with friction velocity. Soil temperatures on the other hand only explained about 8% of the variance. The best agreement (r^2_{adj} = 0.68) of modeled and measured data was obtained by a model which included an exponential term that accounts for the observed influence of air pressure.

Thaw depth, which increased gradually and without variation throughout the season, did not improve the model, nor did water level, which remained above the soil surface at all times in the polygon centers.

The cumulative methane emission during the 2006 growing season was 1.93 g m^{-2}, which agrees well with the cumulative flux during the same period of a combined 2003 and 2004 dataset that amounted to 1.87 g m^{-2} (Wille et al. 2008). The model underestimated the cumulative measured flux by less than 5%.

Small-scale methane flux

Small-scale methane emission was similar among low-center polygons (Fig. 2) and differed strongly from fluxes at the high-center and rim micro-sites (Fig. 2).

At all three low-center micro-sites, mean daily fluxes in July and August were around 100 mg m^{-2} d^{-1} and decreased at the beginning of September to less than 50 mg m^{-2} d^{-1}, closely following variations in air temperature. When snow started to accumulate between September 10 and 15 during a period of below-zero temperatures, emissions fluctuated below 20 mg m^{-2} d^{-1}. At polygon 4, the seasonal course was less pronounced and variability was less extreme than at polygon 1 and 3, where peak fluxes exceeded 350 mg m^{-2} d^{-1} and were associated with spatial standard deviations of up to ±300 mg m^{-2} d^{-1}, demonstrating a large spatial variability even within micro-sites. These extreme emissions were generally associated with high temperatures.

It was not possible to construct a multidimensional regression model with independent and significant parameters. The predictor variable with the highest explanatory power within the final one-dimensional model was surface temperature.

At polygon 2 (high center) and at the polygon rim, very low methane concentrations in the closed chamber system frequently caused the analyzer to reach its detection limit, resulting in noisy data and a high exclusion rate during flux calculation. Fluxes that could be calculated were very low throughout the campaign and rarely exceeded 10 mg m^{-2} d^{-1}, which is about 10% of the average fluxes from low-center polygon micro-sites. No seasonal course is evident from the data and no statistically significant correlation with any of the observed environmental parameters was found. Gaps in the time series were filled with monthly average flux values, accounting for the small positive fluxes that were present.

Averaging closed chamber methane fluxes from wet polygon centers and drier sites, respectively, and weighing them according to the distribution of wet (40%) and drier (60%) surfaces classes results in an up-scaled closed chamber flux of 39.11 mg m^{-2} d^{-1}, which is double the eddy covariance flux during the same time period.

Discussion

Discussion

Results from eddy covariance measurements differ from closed chamber data both in terms of the seasonal variation and the identified controls on methane emissions. While ecosystems scale fluxes do not show much of a seasonal course, results from low-center polygon closed chambers show a pronounced decrease of methane emission towards the end of the season, which is more in agreement with most studies and results from deterministic process-based models used for larger scale modeling (Kirschke et al. 2008).

Emission peaks also do not match on the different scales. While ecosystem scale emission peaks usually coincide with high wind speed, low air pressure, and generally "bad weather" conditions, the largest emission from polygon centers as measured by closed chambers occurred during warm and dry days. However, the very weak peaks visible in closed chamber data from the rim and high-center micro-site tend to be more in agreement with eddy covariance emission peaks.

These differences in the seasonal dynamics may partly be explained by the very different hydrological conditions of the investigated micro-sites in combination with the importance of plant-mediated transport of methane (Kutzbach et al. 2004): in the wet polygon centers, water levels were always at or above the soil surface. Here, higher water levels could lead to decreased methane emission, as more vegetation becomes submerged and plant-mediated transport decreases. In addition, higher temperatures likely increase microbial methane production close to the surface. Hence, warm weather and falling water levels could actually increase emissions as long as the water table remains above the surface. At "drier" micro-sites, on the other hand, storm systems with strong precipitation events lead to a temporary increase in anaerobic soil volume and an increase in methane production, while lower temperatures have a negative effect on the activity of methane oxidizing microbes in the upper horizons of the active layer.

However, a large influence on the ecosystem methane flux can also be ascribed to open-water surfaces such as polygon ponds and thermokarst cracks, which were not covered by the closed chamber measurements but were present in the eddy covariance footprint. Diffusive and turbulent gas transfer between water and atmosphere is known to be proportional to the third power of the wind speed (Wanninkhof & McGillis 1999) and observation of methane ebullition (Walter et al. 2006) in the field indicates that water bodies are an important contributor to ecosystem methane efflux. These micro-sites must be included in future small-scale measurements within the eddy covariance footprint in order to more accurately scale chamber flux measurements to larger areas. A more detailed analysis of the small-scale variability and the scaling problems is in preparation.

The discrepancies in the results on the different scales also highlight the need for more non-intrusive and spatially integrating measurements from high-latitude ecosystems to verify and understand the results produced by the eddy covariance method. Larger scale methane emission models that have previously been developed on the basis of closed chamber data only, should incorporate new findings from eddy covariance or other non-intrusive techniques.

Our findings raise the question to which extent methane fluxes in permafrost ecosystems are controlled by near-surface controls including atmospheric boundary layer conditions and vegetation, or by soil characteristics and processes in the deeper active layer including microbial community structure and activity.

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References

Boike, J., Hinzman, L.D., Overduin, P.P., Romanovsky, V., Ippisch, O. & Roth, K. 2003. A comparison of snow melt at three circumpolar sites: Spitsbergen, Siberia, Alaska. *Proceedings of the Eighth International Conference on Permafrost, Zürich, Switzerland*: 79-84 pp.

Boike, J., Wille, C. & Abnizova, A. 2008. The climatology and summer energy and water balance of polygonal tundra in the Lena River Delta, Siberia. *J. Geophys. Res.* (in press).

Christensen, T. R., Friborg, T., Sommerkorn, M., Kaplan, J., Illeris, L., Soegaard, H., Nordstroem, C. & Jonasson, S. 2000. Trace gas exchange in a high-arctic valley 1. Variations in CO_2 and CH_4 flux between tundra vegetation types. *Global Biogeochem. Cycles* 14(3): 701-714.

Fan, S.M., Wofsy S.C., Bakwin P.S., Jacob D.J., Anderson S.M., Kebabian P.L., McManus J.B., Kolb C.E. & Fitzjarrald D.R. 1992. Micrometeorological measurements of CH_4 and CO_2 exchange between the atmosphere and subarctic tundra. *J. Geophys. Res.* 97(D15): 16,627-16,643.

Friborg, T., Christensen T.R., Hansen B.U., Nordstroem C. & Soegaard H. 2000. Trace gas exchange in a high-arctic valley: 2. Landscape CH_4 fluxes measured and modeled using eddy correlation data. *Global Biogeochem. Cycles*, 14(3): 715–724.

Grigoriev, N.F. 1960. The temperature of permafrost in the Lena delta basin – deposit conditions and properties of the permafrost in Yakutia. *Yakutsk*, 2: 97-101.

Harazono, Y., Mano, M., Myiata, A., Yoshimoto, M., Zulueta R.C., Vourlitis G.L., Kwon H. & Oechel W.C. 2006. Temporal and spatial differences of methane flux at arctic tundra in Alaska. *Mem. Natl. Inst. Polar Res.*, Spec. Issue 59: 79-95.

Hargreaves, K.J., Fowler, D., Pitcairn, C.E.R. & Aurela M. 2001. Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements. *Theor. Appl. Climatol.*, 70: 203-213.

Kirschke, S., Guenther, K.P., Wisskirchen, K., Sachs, T. & Dech, S. 2008. Methane Emission from Siberian Wet Polygonal Tundra on Multiple Spatial Scales: Process-based Modeling of Methane Fluxes on the Regional Scale, Lena Delta. (this proceeding)

Kotlyakov, V. & Khromova T. 2002. Permafrost, snow and ice. In: *Land Resources of Russia*. CD-ROM. V. Stolbovoi & I. McCallum (eds.), International Institute of Applied Systems Analysis and the Russian Academy of Science, Laxenburg, Austria.

Kutzbach, L., Wagner D. & Pfeiffer E.-M. 2004. Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia. *Biogeochemistry* 69: 341-362.

Kutzbach, L. 2006. The exchange of energy, water and carbon dioxide between wet arctic tundra and the atmosphere at the Lena River Delta, Northern Siberia. *Reports on Polar and Marine Research* 541.

Kutzbach, L., Wille, C. & Pfeiffer, E.-M. 2007. The exchange of carbon dioxide between wet arctic tundra and the atmosphere at the Lena River Delta, Northern Siberia. *Biogeosciences* 4: 869-890.

Liebner, S. & Wagner, D. 2007. Abundance, distribution and potential activity of methane oxidizing bacteria in permafrost soils from the Lena Delta, Siberia. *Environmental Microbiology* 9(1): 107-117.

Reeburgh, W.S., King J.Y., Regli S.K., Kling G.W., Auerbach N.A. & Walker, D.A. 1998. A CH_4 emission estimate for the Kuparuk River basin, Alaska. *J. Geophys. Res.* 103(D22): 29,005-29,014.

Sachs, T., Wille, C., Boike, J. & Kutzbach, L. 2008. Environmental controls on ecosystem-scale CH_4 emission from polygonal tundra in the Lena River Delta, Siberia. *J. Geophys. Res.* in press.

Schuchard-Ficher, C., Backhaus, K., Humme, U., Lohrberg, W., Plinke, W. & Schreiner, W. 1982. *Multivariate Analysemethoden. Eine anwendungsorientierte Einführung*. Berlin, Heidelberg, New York: Springer-Verlag, 346 pp.

Schuepp, P.H., Leclerc M.Y., MacPherson J.I. & Desjardins R. L. 1990. Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. *Boundary-Layer Meteorology* 50(1-4): 355-373.

Schwamborn, G., Rachold, V. & Grigoriev, M.N. 2002. Late Quaternary sedimentation history of the Lena Delta. *Quaternary International* 89: 119-134.

Soil Survey Staff. 1998. *Keys to Soil Taxonomy 8th Edition*. Blacksburg, Virginia: Soil Conservation Service.

Walter, K.M., Zimov, S.A., Chanton, J.P., Verbyla, D. & Chapin III, F.S. 2006. Methane bubbling from thaw lakes as a positive feedback to climate warming. *Nature* 443: 71-75.

Wanninkhof, R. & McGillis, W.R. 1999. A cubic relationship between air-sea CO_2 exchange and wind speed. *Geophysical Research Letters* 26(13): 1889-1892.

Whalen, S.C. & Reeburgh, W.S. 1992. Interannual variations in tundra methane emission: A 4-year time series at fixed sites, *Global Biogeochem. Cycles* 6(2): 139-159.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D. & Pfeiffer, E.-M. 2008. Methane emission from Siberian arctic polygonal tundra: Eddy covariance measurements and modeling. *Global Change Biology* (in press).