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Modelling CH_4 emissions from arctic wetlands: effects of hydrological parameterization

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Abstract. This study compares the CH_4 fluxes from two arctic wetland sites of different annual temperatures during 2004 to 2006. The PEATLAND-VU model was used to simulate the emissions. The CH_4 module of PEATLAND-VU is based on the Walter-Heimann model. The first site is located in northeast Siberia, Indigirka lowlands, Kytalyk reserve (70° N, 147° E) in a continuous permafrost region with mean annual temperatures of -14.3°C. The other site is Stordalen mire in the eastern part of Lake Torneträsk (68° N, 19° E) ten kilometres east of Abisko, northern Sweden. It is located in a discontinuous permafrost region. Stordalen has a sub arctic climate with a mean annual temperature of -0.7°C. Model input consisted of observed temperature, precipitation and snow cover data.

In all cases, modelled CH_4 emissions show a direct correlation between variations in water table and soil temperature variations. The differences in CH_4 emissions between the two sites are caused by different climate, hydrology, soil physical properties, vegetation type and NPP.

For Kytalyk the simulated CH_4 fluxes show similar trends during the growing season, having average values for 2004 to 2006 between 1.29–2.09 $\mathrm{mg\,CH_4\,m^{-2}\,hr^{-1}}$. At Stordalen the simulated fluxes show a slightly lower average value for the same years (3.52 $\mathrm{mg\,CH_4\,m^{-2}\,hr^{-1}}$) than the observed 4.7 $\mathrm{mg\,CH_4\,m^{-2}\,hr^{-1}}$. The effect of the longer growing season at Stordalen is simulated correctly.

Our study shows that modelling of arctic CH_4 fluxes is improved by adding a relatively simple hydrological model that simulates the water table position from generic weather data. Our results support the generalization in literature that CH_4 fluxes in northern wetland are regulated more tightly by water table than temperature. Furthermore, parameter uncertainty at site level in wetland CH_4 process models is an important factor in large scale modelling of CH_4 fluxes.

1 Introduction

Together with water vapour and carbon dioxide (CO_2), methane (CH_4) is an important contributor to the warming of the atmosphere. The atmospheric mixing ratios of so called greenhouse gases, CO_2, and nitrous oxide (N_2O) have increased about 31%, and 17%, respectively above pre-industrial values whereas CH_4 has increased 151%±25%, (IPCC, 2001).

The CH_4 abundance in 2005 of about 1774 ppb is more than double its pre-industrial value.Increases in atmospheric CH_4 concentrations since pre-industrial times have contributed a radiative forcing of $+0.48\pm0.05\,\mathrm{Wm^{-2}}$. Current atmospheric CH_4 levels are due to continuing anthropogenic emissions of CH_4, which are greater than natural emissions. Emissions from individual sources of CH_4 are not as well quantified as the total emissions but are mostly biogenic and include emissions from wetlands, ruminant animals, rice agriculture and biomass burning, with smaller contributions from industrial sources including fossil fuel-related emissions (Solomon et al., 2007).

About 60% of global CH_4 emissions come from human-influenced sources and the rest are from natural sources (IPCC, 2001). Natural sources include wetlands, termites, oceans, and hydrates. Natural sources are dominated by wetlands. Where soils are waterlogged and oxygen is absent,

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methanogenic micro-organisms produce large amounts of CH_4 as they respire organic matter to CO_2 to derive energy. Wetland CH_4 emissions are thought to comprise around 80 percent of the total natural CH_4 source. Total annual CH_4 emissions from natural sources are estimated to be around 250 Tg (Reay, 2006).

In the past decade the overall annual rate of CH_4 growth has decreased and become highly variable (Dlugokencky et al., 2003; Ciais et al., 2005). Ciais et al. (2005) attributes the decrease to a temporary reduction in anthropogenic emissions and the increased variability to wetland emission distribution. The largest CH_4 atmospheric mixing ratios are north of 40° N (Steele et al., 1987). This distribution coincides with the concentration of wetlands in the northern hemisphere and suggests that wetlands in this area may make a significant contribution to the global CH_4 budget (Moore and Knowles, 1990; Aselmann and Crutzen, 1989; Crill et al., 1988; Matthews and Fung, 1987).

The magnitude of the CH_4 emissions from wetlands is controlled by the dynamic balance between CH_4 production and oxidation rates in the peat profile and by transport mechanisms (Bubier and Moore, 1994). Measured emissions demonstrate high spatial and temporal variation (Moore et al., 1990; Whalen and Reeburg, 1992; Dise, 1993) linked to environmental factors such as variation in temperature and ground water level.

CH_4 production and oxidation rates depend on substrate availability and supply, temperature and activity of the CH_4-producing and CH_4-oxidizing bacteria, affected by the redox status in the soil matrix which in turn is linked to the soil moisture condition and hydrochemistry (Kettunen et al., 1999). Changes in both substrate availability and oxidation state during the growing season affect the population dynamics of methanogenic and methanotrophic bacteria (Svensson and Rosswall, 1984; Whiting and Chanton, 1993) and are reflected in the net CH_4 flux (Kettunen et al., 1999).

The water table in many wetlands show a seasonally related variation, with low levels in midsummer when the evapotranspiration is high and high levels in the rest of the season when precipitation dominates. The amount of variation depends on the water sources of the wetland (precipitation, groundwater or surface water flow). Because of the presence of microtopography (hummocks, hollows and lawns, Bubier et al., 1993b) the topography of a wetland has a very high spatial variability which determines also spatial variability in CH_4 fluxes. Bubier et al. (1993b) found that the CH_4 flux follows the trend: hollows > lawns > hummocks. The hollows have a much higher CH_4 emission than the other microrelief features. The same holds for sedge lawns and wet parts of river floodplains (Van Huissteden et al., 2005). A characteristic of high latitude wetlands is the presence of the permafrost. Studies have shown that approximately 14% of the global carbon is stored in permafrost soils and sediments (Post et al., 1982). The frozen subsoil contributes to waterlogged soil conditions in permafrost wetlands. However, observations have shown that permafrost degradation causes an increase of CH_4 fluxes by changes in local hydrology and ecosystem balance. More widespread thaw across the discontinuous permafrost region will be an important consideration to boreal C budgets with future climate change (Turetsky et al., 2002). Adequate modelling of these processes requires first of all correct modelling of the effects of water table on CH_4 fluxes. Models also should perform well in situations where ground water table observations are not available.

The purpose of this study is to quantify/study the effect of water table, temperature and different vegetation types at two high latitude wetland sites on CH_4 emission, by means of field measurements and a modeling approach that combines the CH_4 flux process approach of Walter (2000) with the soil physics as included in the model of Granberg et al. (1999). The study is based on site soil physical, vegetation and water level data. The CH_4 flux measurements at the sites have been used to validate the model. Model runs have been made with both site water level observations and modelled water levels based on generic weather data, to compare the influence of modelled or observed water tables on model performance.

2 Material and methods

2.1 Site description

Kytalyk. The study area on which the research was based on is located in Northeastern Siberia, in the Kytalyk reserve, in the Indigirka lowlands near Chokhurdagh (70°48′ N, 147°26′ E, elevation 48 m). The research area consists of three different morphological units: the river floodplain, the river terrace with tundra vegetation and the high plateaus (10–30 m) underlain by continuous permafrost. The area is characterized by silty soils with a peaty topsoil. The study site is located in river lowlands consisting of fluvial terraces of Late Pleistocene and Holocene age, and the recent floodplain of a meandering river with extensive backswamps situated behind natural levees. Next to the floodplain, a terrace (Holocene age) approximately 2 m above the present floodplain is found, consisting of a drained thermokarst lake floor, with hummocky moist tundra in the dryer parts and a mature network of low-centred ice wedge polygons in the lower parts. The next higher level in the landscape consists of so-called "ice complex" hills, which probably represent a higher Pleistocene terrace. The CH_4 flux measurements were confined to the lower terrace and the river floodplain. The climate is high arctic, with an annual average temperature measured at the Chokhurdagh airport weather station of −14.3 degrees Celsius, the warmest month being July, the coldest January (data derived from NOAA website and summarized by Van Huissteden et al., 2006b). The source for the air temperature, precipitation and snow data were the local site measurements in summer, supplemented with data from the

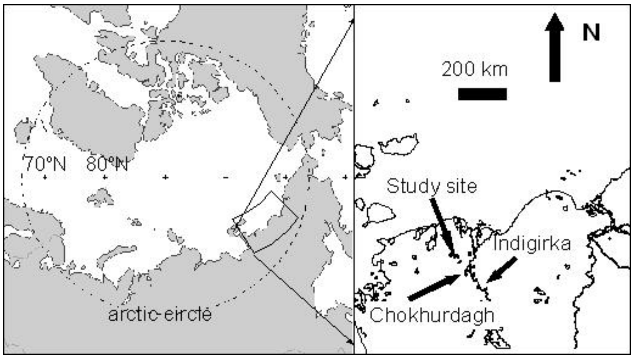

Fig. 1. Location of the study site, Kytalyk Reserve, NE Siberia (modified after Van Huissteden et al., 2006a).

Chokhurdagh airport weather station. Missing values were interpolated (Fig. 1).

At Kytalyk, the vegetation of the lower terrace/drained thaw lake consists mainly of ombrotrophic *Sphagnum* mire, alternating with interconnected depressions dominated by sedges and *Eriophorum*. On the dryer parts *Betula nana*, *Salix* and *Eriophorum* hummocks dominate. On the river floodplain vegetation varies from *Carex*/*Eriophorum* fen with grasses in wide backswamp areas, to *Salix* shrub on levees. The active layer ranges from 18 cm at dry, *Sphagnum*-covered sites on the terrace, to up to 53 cm in some parts of the floodplain. Thermokarst processes are active along the river bank and thermokarst lake banks.

Stordalen. The Stordalen Mire (68°21′ N, 19°02′ E, elevation 360 m a.s.l.) is situated at about 10 km east of Abisko Scientific Research Station, Sweden (Öquist et al., 2001). This mire was part of the International Biological Programme, and has been studied since early 1970s. The site is about one kilometer from and ten meters above Lake Torneträsk (Fig. 2).

The entire Stordalen mire is 25 ha large and is treeless. It is made up of four major habitats: (1) elevated, nutrient-deficient (ombrotrophic) areas with hummocks and small shallow depressions; (2) wet, nutrient-richer (minerotrophic) depressions; (3) pools and (4) brooks bringing water to and from the complex (Rooswall et al., 1975). With regard to the permafrost and the plant cover composition, the site is a typical northern peatland. The elevated parts are on permafrost and have tundra like vegetation (Rooswall et al., 1975). The climate is subarctic, with a mean annual temperature of −0.7°C, the warmest month being July and coldest February. The annual precipitation at Abisko is the lowest in the northern part of Sweden, about 300 mm (records from 1913–2003).

This study focuses on a wet minerotrophic area of the mire, where the water table is situated in the vicinity of the soil surface and the vegetation is dominated by *Eriophorum angustifolium.* In the drier parts of the mire the *Eriophorum vaginatum* and *Carex rotundata* dominates the *Sphagnum* spp. (Öquist and Svensson 2001).

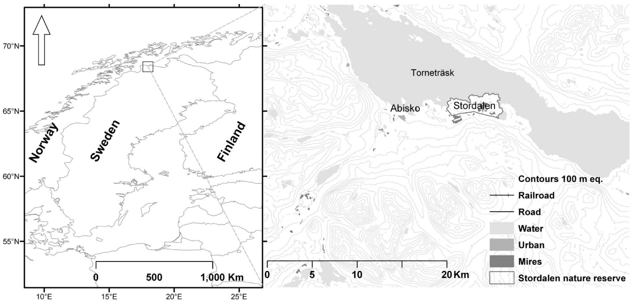

Fig. 2. Location of the study site, Stordalen mire, N Sweden (from Bäckstrand et al., 2008).

2.2 Measurements

2.2.1 CH_4

Kytalyk. During 2004–2006, the CH_4 fluxes were measured in Kytalyk in short (few days) field campaigns during the summer period. The flux measurements were made using closed chambers, in a roving manner, in order to sample a wider variety of vegetation type and hydrologic conditions (Van Huissteden et al., 2005; van der Molen et al., 2007).

Stordalen. In 2004 and 2005, CH_4 fluxes were measured using an automatic chamber system at Stordalen, described in Bäckstrand et al. (2008). The automatic system also allowed for manual sampling. The manually sampled air was analyzed for CH_4 and the resolved CH_4 fluxes were used in this study. The chambers were placed on both wet and dry part of the mire but only the data from the chambers on the wet part were used. In 2006, the CH_4 fluxes were measured using the data from the eddy correlation (EC) tower (Christensen et al., 2004). The EC measurements of CH_4 exchange have been conducted with the use of a cryo-cooled fast IR gas analyzer Tunable Diode Laser Trace Gas Detector (Aerodyne Res., Inc) coupled with a 3D sonic anemometer (R2, Gill instruments Ltd, 3 m above peat surface).

2.2.2 Water table measurements and simulations

Kytalyk. The ground water table was determined after the flux measurements took place, from a hand auger hole. During the summer of 2004 daily values were recorded during four consecutive days (27–31 July) (Van Huissteden et al., 2005). For the year, 2005, measurements took place between 20 and 30 July. In 2006 the water table was measured from 15 to 18 August.

Stordalen. Water table position relative to ground level was measured manually 3–5 times per week at all sites

(Bäckstrand et al., 2008). For the purpose of this study and to match with the CH_4 fluxes, only the data from the wet part of the mire were used.

2.3 Model description

2.3.1 The PEATLAND-VU Model

PEATLAND-VU is a process-based model of CO_2 and CH_4 emission from peat soils at various management scenarios. It includes a slightly modified version of the Walter (2000) soil profile scale CH_4 flux model (Van Huissteden et al., 2006a) and a simplified soil physical model to simulate soil temperatures and soil freezing/thawing.

It consists of four submodels: a soil physics submodel to calculate temperature, water saturation and ice content of the soil layers, a CO_2 submodel, a CH_4 submodel and an organic production submodel (Van Huissteden et al., 2006a).

The CH_4 submodel is based on Walter et al. (1996), Walter (2000) and Bogner et al. (2000). The model of Walter (2000) includes: (1) CH_4 production depending on substrate availability; (2) CH_4 oxidation within the aerated soil topsoil and in plant roots and stems; (3) CH_4 transport by diffusion above and below the water table; (4) transport by ebullition below the water table; and (5) transport through plants (Van Huissteden et al., 2006a). For this study we only used PEATLAND-VU to estimate CH_4 fluxes.

The model requires as input a soil profile description with organic matter content, dry bulk density and pF curves for each soil horizon, and time series for soil surface or air temperature, water table depth and snow cover for each model time step (1 day in this study). Output of the model is the surface CH_4 fluxes, including contributions from the different transport pathways.

2.3.2 Input data and parameterization of the model

The input data for PEATLAND-VU Model can be obtained from generic data, e.g. soil profiles and weather data stations (Van Huissteden et al., 2006a). Some soil parameters, e.g. initial conditions for the amount of carbon stored in different soil organic matter reservoirs (peat, labile and resistant organic matter reservoirs) and their decomposition rates are difficult to measure without more extensive soil organic mater analysis facilities and need estimation from literature (e.g. Rooswall et al., 1975). For the Kytalyk site there is no quantitative data available yet on soil organic matter content due to logistic reasons; therefore we use comparable organic matter content data from the Swedish site. The PEATLAND-VU model CH_4 simulations are not very sensitive to the exact soil composition (Van Huissteden et al., 2006a). Parameters for the CH_4 model that need calibration are the CH_4 production rate R_0 (Walter, 2000); in practice also the oxidation of CH_4 during plant transport is also a poorly quantified parameter that may need calibration (Van Huissteden et al., 2006a). Based on the input data, simulations were carried out and the output CH_4 fluxes were compared with the measured ones (only for the Kytalyk site: three values represented with error bars). All input data (climate, soil parameters, vegetation type and ground water depth) were based on observations at the sites.

For 2004 to 2006, the Stordalen climatic data sets were provided by the Abisko Scientific Research Station. For Kytalyk the data were obtained from Chokhurdagh weather station at the local airport. In addition, air and soil temperature data measured on the site for micrometeorological CO_2 and H_2O flux measurements were used (van der Molen et al., 2007). Several parameters influence the simulations and were calibrated. The most important ones were: the CH_4 production rate R_0 was set at the low end of the range indicated by Walter (2000) (Van Huissteden et al., 2006a).

2.3.3 Water table simulations

The ground water table strongly influences the CH_4 fluxes. Two runs were performed with two different water table files. The first was the measured water table and the second was simulated using equations based on the Mixed Mire Water and Heat Model (MMWH) of Granberg et al. (1999) as modified by Yurova et al. (2007). The hydrology of the model is represented by a simple bucket approach describing the change in water content of a unit area (Granberg et al., 1999). The MMWH model was developed to reconstruct the water table position in the upper active layer of the boreal mixed mires. This approach is based on the steady state moisture distribution in the unsaturated zone, which is simulated by the van Genuchten functions (1980) simplified and parameterized for the peat of different types by Weiss et al. (1998). The lateral flow is modelled dynamically, including the transmissivity feedback: the increase in runoff associated with higher water table due to change in hydraulic conductivity (maximum at the surface and reduces strongly with depth). Calculated potential evapotranspiration is reduced when the water table drops below the peat surface, and this decrease is exponential with a water table depth. The depth of permanent saturation and peat composition and physical properties are the main site-specific model parameters.

3 Results

3.1 Annual climate variations

Stordalen. The variation in climate parameters for 2004–2006 is shown in Fig. 3. The average value for air temperature was 1.07°C, the coldest day being the 3 March 2006 (−29.36°C) and warmest the 5 July 2005 (19.69°C). The data were provided by the Abisko Scientific Research Station for the three years in study. Abisko is in the rain shadow of the Norwegian mountains and the precipitation received is among the lowest in Scandinavia (Johansson et al., 2006).

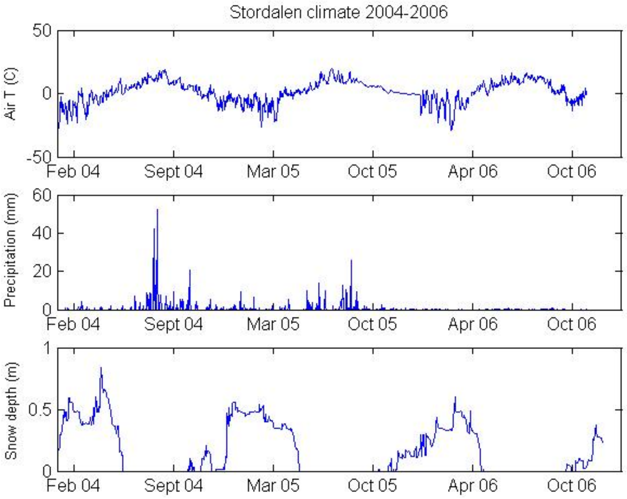

Fig. 3. Three years weather data records from the Stordalen Mire (source: Abisko Scientific Research Station).

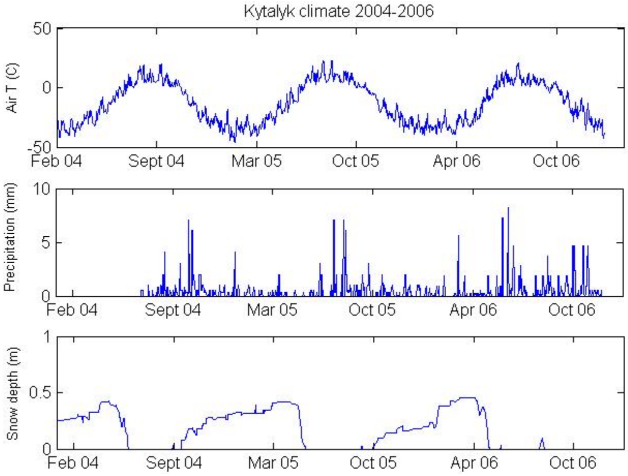

Fig. 4. Three years weather data records from the Kytalyk site derived from Chokhurdagh airport weather station (source: NOAA-NCDC website http://lwf.ncdc.noaa.gov/oa/ncdc.html, augmented with local summer measurements).

The total amount of precipitation for the period 2004–2006 is only 612 mm. The gaps in data for the soil temperature at 3 cm depth were due to the malfunction of the instrument.

The winter precipitation is mainly snow. The mean snow depth on the Stordalen mire was during this period 0.18 m. This is different from Abisko, due to snowdrift effects in the open space of the Stordalen mire. The soil temperature records were measured at Stordalen mire.

Kytalyk. Figure 4 shows the three years record for climate parameters at the Siberian site. The mean temperature for the three years was −12.8°C, the coldest day being 12 December 2004 and the warmest 4 July 2005.

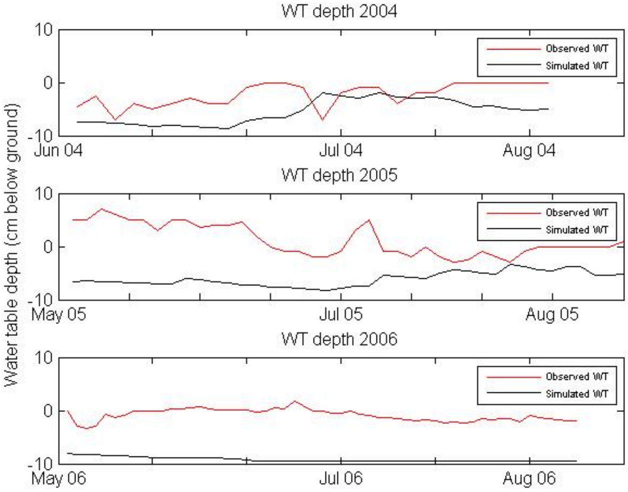

Fig. 5. Water table depth from the wet part of the Stordalen Mire for 2004–2006. Measured values in red and simulated in black.

3.2 Water table and active layer measurements

Stordalen. For this study the water levels from the fen portion of the mire were used, as presented in Fig. 5.

The active layer was measured at Stordalen mire at different sites, from 17.06–20.09.2004 and on the 22.09.2005 at 121 sites. The mean value for the year 2004 was 50.67 cm and for 2005 was 66.6 cm.

Kytalyk. The water table measurements (Table 2 and Fig. 6) were made during the field campaigns. We used the average water table for the floodplain sites to interpolate between periods with modelled water table. In Table 2 the averaged values (7 point measurements in 2004, 21 in 2005 and 12 in 2006 from the floodplain wet area) are shown.

Using as input parameters the climate data, we modelled the water table with the MMWH model (Granberg et al., 1999, modified by Yurova et al., 2007). Figure 5 shows the simulation for Stordalen mire and Fig. 6 for Kytalyk site.

The deviations between data and model for the Stordalen simulations is within the maximum range of deviations of 10 cm as reported in Granberg et al. (1999). The reason is that the MMWH model tends to underestimate the higher water tables and overestimate the lower ones. Partly this may be caused by inaccuracies of the water table caused by vertical movements of the mire surface together with the varying water table (Fritz et al., 2007). In particular for 2006 the model underestimates the water table. The year 2006 had a low amount of precipitation; possibly the water table was maintained by groundwater input which is not included in the model.

The cause of the deviation between data and model for the Kytalyk simulations is the excessive drainage of the floodplain caused by an abnormal low water level of the river water in 2005.

Table 1. Soil physical parameters per soil horizon as used in the PEATLAND-VU Model (Van Huissteden et al., 2006a; Rosswall and Heal, 1975).

Soil physical parameters per soil horizon	Kytalyk (estimated data)	Stordalen (measured data)
Number of horizons	3	4
Horizons depths with respect to surface (in meters)	[0.1, 0.2, 2.0]	[0.1, 0.2, 0.3, 2.0]
C/N ratios for each soil layer	[15, 15, 15]	[48, 38, 31, 15]
Dry bulk density for each horizon (kg m^{-3})	[100, 130, 975]	[88, 102, 519, 808]
Percentage organic matter for each horizon	[95.0, 80.0, 5.0]	[90.0, 80.0, 70.0, 5.0]
pH	[6.0, 6.0, 7.0]	[4.0, 4.0, 4.1, 4.0]

Table 2. Average water table depth and active layer thickness (cm below ground) from the floodplain wet area in Kytalyk for the years 2004–2006.

Year	Average water table (cm below surface)	Average active layer thickness cm
2004	0.71	42.8
2005	2.8	42.5
2006	0.16	53.5

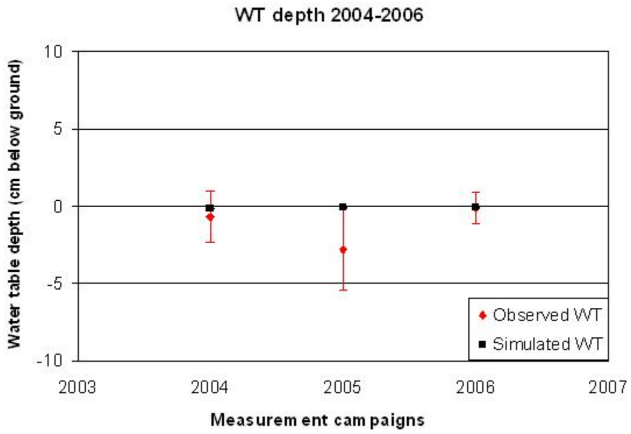

Fig. 6. Floodplain water table depth modelled with the MMWH Model for Kytalyk site 2004–2006. Measured values in red and simulated in black.

3.3 CH_4 fluxes

The PEATLAND-VU model was run for the two sites and tuning eye was performed for the most sensitive parameters: the CH_4 production rate R_0, Q_{10} and plant oxidation type. For Kytalyk the values for R_0 was set to 0.3 μMh^{-1} and for Stordalen to 0.25 μMh^{-1} for both WT approaches; the Q_{10} value for temperature correction CH_4 production (range 1.7–16 in Walter and Heimann, 2000) was set at a value of 4 for the Swedish site and 2 (simulations with observed WT) and 3 (simulations with simulated WT) for the Siberian site; and the CH_4 plant oxidation fraction was set 0.6 for the Siberian site and 0.7 for the Swedish site. For a better estimation of R_0 and Q_{10} and to double check the tuning, parameter estimation for Q_{10} and R_0 test was carried out. The best fit between the two parameters was Q_{10} value 4.4 and R_0 value 0.22, close to the used parameters (Fig. 7).

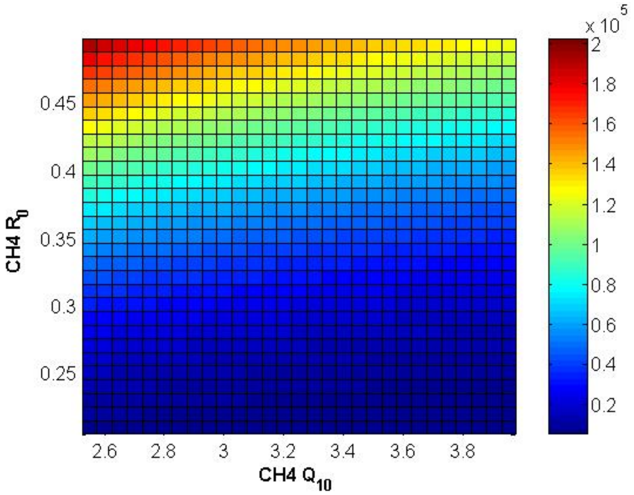

Fig. 7. Parameter estimation for the CH_4 production Q_{10} and R_0 values of the model for Stordalen. The grid cells of the figure indicate the squared deviations of the model from the data.

Stordalen. Using the measured water table depth from the fen part of the Stordalen Mire, the CH_4 flux trend is similar to the simulated one. The range for the measured CH_4 is between 0 mg m^{-2} hr^{-1} and 18.07 mg m^{-2} hr^{-1} (average value of 4.7 mg m^{-2} hr^{-1}), while the simulated emissions vary between 0 mg m^{-2} hr^{-1} and 26.9 mg m^{-2} hr^{-1}, with an average value for the three years of 3.52 mg m^{-2} hr^{-1} (Fig. 8).

A second run, using the simulated water table from the changed version of Granberg et al., 1999, was performed with the PEATLAND-VU model. The CH_4 fluxes show a

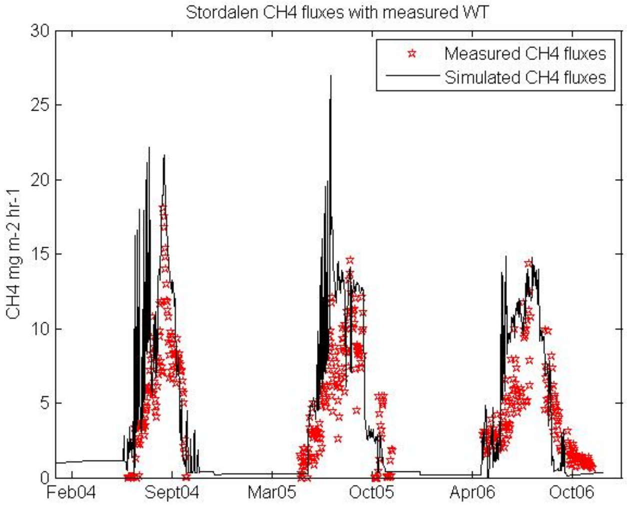

Fig. 8. Measured (red) and simulated (black) CH_4 emissions from the wet part of the Stordalen Mire for 2004–2006 with measured water table (see Fig. 5).

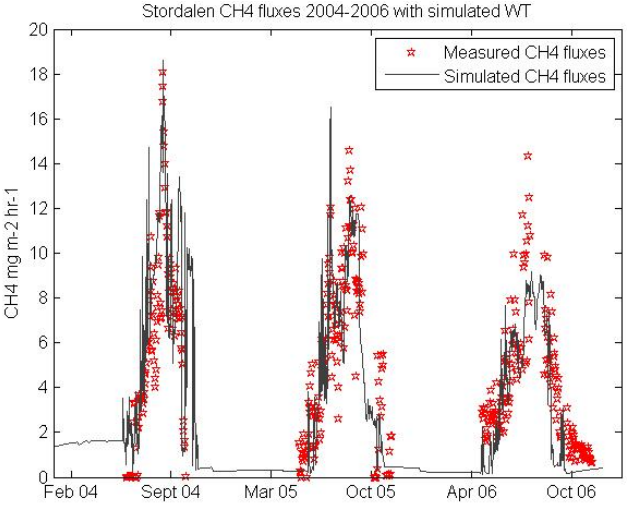

Fig. 9. Measured (red) and simulated (black) CH_4 emissions from the wet part of the Stordalen Mire for 2004–2006 with simulated water table (see Fig. 5).

very similar pattern for the years 2004 to 2006 (see Fig. 9). The measured CH_4 emissions from the fen portion of the mire, averaged a value of $4.7\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ (data from two chambers for the 2004 and 2005 years and measured data with TDL from the EC tower for 2006) and range between $0\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ and 18.07 mg while the simulated fluxes range between $0\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ and $18.54\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ with averaged value of $2.53\,\mathrm{mg\,m^{-2}\,hr^{-1}}$. The CH_4 flux peak in both model and data was during the same month (September) and the period with active emission coincides with the growing season (April–October).

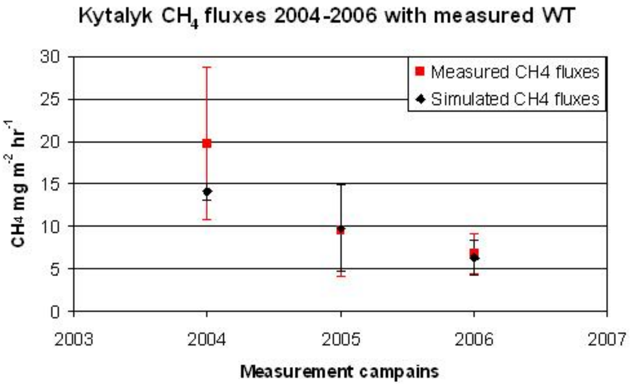

Fig. 10. Average measured value (red) and simulated (black) CH_4 emissions for 2004–2006 at Kytalyk site using the floodplain measured water table from Table 2.

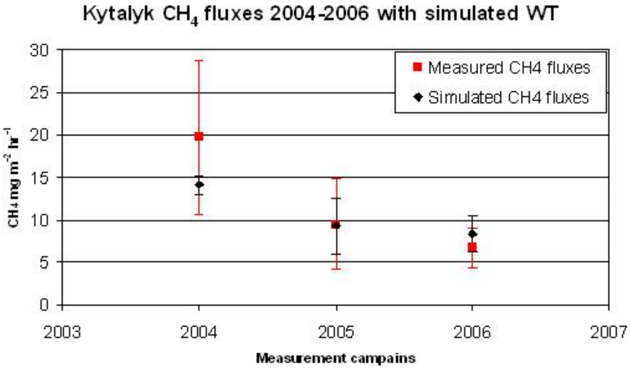

Fig. 11. Average measured value (red) and simulated (black) CH_4 emissions for 2004–2006 at Kytalyk site using the floodplain simulated water table from Fig. 6.

Kytalyk. For Kytalyk the measurements for the water table depth were done for four consecutive days in 2004, 10 days in 2005 and four day in 2006. Due to the very remote area it was not possible to perform yearly measurements, therefore the water table input file used by PEATLAND-VU was constructed based on the available data and on the assumption that the minimum water depth is 5 cm below ground and does not exceeds 15 cm depth during winter time. The active layer was simulated with PEATLAND-VU based on the output temperature file constructed by the model using the air temperature as input. The soil physical submodel tends to overestimate the active layer depth. However, the measured active layer average value at the wet sites (0.45 cm) is within the range of the simulated ones (0.05–0.85 m).

The CH_4 fluxes range between $0\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ and $20.8\,\mathrm{mg\,m^{-2}\,hr^{-1}}$ with a three year average value of $1.29\,\mathrm{mg\,m^{-2}\,hr^{-1}}$. For the 2005 and 2006 the averaged value matches with the simulations. The only exception is for the year 2004 when the measurement exceeds the simulation but it is with the error measurements (Fig. 10).

Table 3. List of calibrated parameters used in PEATLAND-VU runs for the two sites.

	Kytalyk calibrated parameters		Stordalen calibrated parameters	
	Model runs with observed WT	Model runs with simulated WT	Model runs with observed WT	Model runs with simulated WT
R_0	0.3 μMh-1	0.3 μMh-1	0.25 μMh-1	0.25 μMh-1
Q_{10}	2	3	4	4
P_{ox}	0.7	0.7	0.7	0.7

The results show a good match with the averaged point measurements when Peatland-VU was run with the simulated water table (Fig. 11). The fluxes vary between 0 mg m^{-2} hr^{-1} and 26 mg m^{-2} hr^{-1}, with a three year average flux of 2.09 mg m^{-2} hr^{-1}. Similar to the simulations carried out with the measured water table, the active layer averaged value (0.45 cm) is within the range of the simulated one (0.05–0.85 m).

4 Discussion

Previous studies show that the CH$_4$ emissions are highly influenced by the water table variation (Van Huissteden et al., 2005). Therefore, for a better estimation of the total CH$_4$ emission from arctic areas, it is necessary to have a very good estimation of the water table depth. Under global warming, permafrost areas are melting and disappearing, as it is the case of Stordalen mire (Christensen et al., 2004).

For the Swedish site, Stordalen, the CH$_4$ emissions on a decadal time scale are mainly influenced by the temperature changes in the past decades, which induced the melt of the permafrost. This results in an increase in the active layer depth and variation in the water table dynamics. Under wetter conditions, the vegetations shifts from shrub dominated, elevated, ombrotrophic conditions to wet graminoid dominated more nutrient rich or minerotrophic conditions (http://www.geography.uc.edu/~kenhinke/CALM). Such a trend is observed at Stordalen but less dramatic than other arctic mires, e.g. Katterjokk, where permafrost has disappeared altogether over the period 1998–2002 (Christensen et al., 2004). The vegetation composition has changed significantly with a decrease in the permafrost-dependent relatively dry elevated mire vegetation types and a corresponding increase in the lower wet graminoid dominated vegetation. This change corresponds to changes in the underlying permafrost distribution as the latter is determining the mire surface topography and hydrology, and hence the plant community structure (Christensen et al., 2004). Due to this change the CH$_4$ emissions increased from 1.8–2.2 mg m^{-2} hr^{-1} (1970) (Christensen et al., 2004) to 4.7 mg m^{-2} hr^{-1} (averaged measured CH$_4$ flux 2004–2006).

The averaged simulated CH$_4$ fluxes for Stordalen range between 3.52 mg CH$_4$ m^{-2} hr^{-1} (measured WT) and 2.53 mg CH$_4$ m^{-2} hr^{-1} (simulated WT), while for Siberia the averaged simulated CH$_4$ fluxes were much lower than the Swedish ones: 1.29 mg CH$_4$ m^{-2} hr^{-1} (measured WT) and 2.09 mg CH$_4$ m^{-2} hr^{-1} (simulated WT).

The mean soil temperature at the Stordalen site, for the years 2004–2006 was +3.76°C, the mean temperature for the three years of measurement at the Siberian site was −12.8°C. The difference in CH$_4$ flux between the two sites reflects the known sensitivity of methanogenesis to temperature and the longer growing season at the warmer Stordalen site (Walter, 2000). However CH$_4$ formation also may occur at subzero temperatures (Rivkina et al., 2000; Wagner et al., 2007) but winter emissions that may occur at negative temperatures are not included in the measurement data and the model.

The optimization of the CH$_4$ model input parameters (CH$_4$ R_0 production rate, Q_{10} value for temperature correction CH$_4$ production) was done by optimizing the values until the optimum match between data and model was found. For both sites the plant oxidation factor was set to a value of 0.7. This means that 70 percent of the CH$_4$ is oxidized during the plant transport. For simulations at Stordalen mire a Q_{10} value of 4 was used, while for Kytalyk the value was set to 2 and 3 for the two water table approaches (see Table 3), the range of it being 1.7–16 (Walter, 2000). Together with R_0, the Q_{10} value influences the peak of the summer emissions relative to early spring and autumn. Since at Kytalyk no data throughout the growing season are available, tuning of the model parameter was focused on R_0 rather than Q_{10}(see Fig. 7). In general, the model is not very sensitive to small differences in the value of Q_{10}. We conclude that the model is more sensitive to the water table than to the temperature. This high sensitivity for water table position agrees well with statistical analysis of CH$_4$ flux data, soil temperatures and water table data from Kytalyk (Van Huissteden et al., 2005).

A good match was observed between the simulated and measured CH$_4$ fluxes using the simulated WT. One of the reasons might be a continuous water table file with constant fluctuations from summer to winter throughout the three years in study. Even if the simulated water table is underestimated by Granberg's model compared to the observations (Fig. 5), the CH$_4$ fluxes match with the measurements.

For the Kytalyk site, the simulated CH$_4$ fluxes match in both approaches with the averaged point measured CH$_4$. The fluxes are much lower than the ones from N Sweden and this may be due to: (1) shorter growing season (May–September) compared with a longer one at Stordalen (April–October), (2) lower soil temperature, (3) more Sphagnum vegetation which lives in symbiosis with metanotrophic bacteria and consumes the CH_4 below the water table (Raghoebarsing et al., 2005) while the Stordalen wet site has *Carex* and *Eriophorum* spp., and (4) differences within the active layer depth.

Vegetation related factors influencing the CH_4 fluxes from floodplain are (1) plant mediated transport of CH_4 between the soils and atmosphere and (2) primary productivity (Van Huissteden et al., 2005). Sedges are good transporters of CH_4 (Busch and Lösch, 1999). The CH_4 fluxes are related to the vegetation since the latter provides substrate for methanogens through root exudation (King and Reeburg, 2002). A recent study at Stordalen shows that sites dominated by *Eriophorum angustifloum* have higher CH_4 fluxes than the ones with *Eriophorum vaginatum* or *Carex rotundata* (Ström and Cristensen, 2007).

The variation within the CH_4 fluxes is strongly influenced by the hydrological conditions at each site. A smoother variation (see Fig. 8) is observed for Stordalen CH_4 as the WT had a more constant trend (not many peaks, Fig. 5). For the Siberian site the water table varied strongly (wet in 2004 and very dry in 2005 caused by the excessive drainage of the floodplain) therefore the emissions show a higher variability in time.

5 Conclusions

CH_4 fluxes from arctic wetlands show a high variability in time and space. Even if both sites are located in arctic areas, the differences are considerable. Both study sites are wetlands but the CH_4 fluxes have different patterns. We hypothesize that the cause for these differences are (1) water table depth (2) air and soil temperature (3) vegetation type and (4) net primary production. By using the simulated water table depth, it was possible to match the measured CH_4 emissions with the simulated ones, using a relatively simple bucket model to simulate the water table based on generic meteorological precipitation and temperature time series. Water table information may not always be available at high measurement resolution and accuracy. We have shown that with the Granberg's model we could simulate the CH_4 flux correctly even with absent (Kytalyk) observations or scattered measurements during the growing season (Stordalen). The results of our study are promising for improvement of regional scale CH_4 emission models. Parameter uncertainty at site level in wetland CH_4 process models is an important factor in large scale modelling of CH_4 fluxes. The CH_4 fluxes at the Kytalyk site appear less sensitive to temperature variation than to water table variation, in concordance with other studies (Moore et al., 1990; Roulet et al., 1991; Walter et al., 1996; van der Molen et al., 2007). This stresses the need for improving hydrological models to correctly simulate water table variations for modelling wetland CH_4 fluxes.

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References

Aselmann, I. and Cruzen, P. J.: Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible CH_4 emissions, J. Atmos. Chem., 8, 307–359, 1989.

Bäckstrand, K., Crill, P. M., Mastepanov, M., Christensen, T. R., and Bastviken, D.: Nonmethane volatile organic compound flux from a subarctic mire in northern Sweden, TellusB, in press, 2008.

Bogner, J. E., Sass, R. L., and Walter, B. P.: Model comparisons of methane oxidation across a management gradient: Wetlands, rice production systems, and landfill, Global Biogeochem. Cy., 14, 1021–1033, 2000.

Bubier, J., Costello, A., Moore, T. R., Roulet, N. T., and Savage, K.: Microtopography and CH_4 flux in boreal peatlands, northern Ontario, Canada, Can. J. Botany, 71, 1056–1063, 1993b.

Bubier, J. L. and Moore, T. R.: An ecological perspective on CH_4 emissions from northern wetlands, Trends in Ecology and Evolution, 9, 409–464, 1994.

Busch, J. and Lösch R.: The gas exchange of Carex species from eutrophic wetlands and its dependence on microclimatic and soil wetness conditions, Phys. Chem. Earth, PT B, 24, 117–120, 1999.

Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., and Loustau, D.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature, Vol. 437 Issue 7058, 529–533, 2 diagrams, 1 graph, doi:10.1038/nature03972; (AN 18373101), 2005.

Christensen, T. R., Johansson, T., Åkerman, H. J., et al.,: Thawing sub-arctic permafrost: effects on vegetation and CH_4 emissions, Geophys. Res. Lett., 31, L04501, doi:10.1029/2003.GL018680, 2004.

Crill P. M., Bartlett, K. B., Hariss, R. C., Gorham, E., Verry, E. S., Sebacher, D. I., Madzar, L., and Sanner, W.: CH_4 flux from Minnesota peatlands, Global Biogeochem. Cy., 2, 371–384, 1988.

Dise, N. B.: CH_4 emissions from Minnesota peatlands: spatial and seasonal variability, Global Biogeochem. Cy., 7, 123–142, 1993.

Dlugokencky, E. J., Houweling, S., Bruhwiler, L., Masarie, K. A., Lang, P. M., Miller, J. B., and Tans, P. P.: Atmospheric CH_4 levels off: Temporary pause or new steady state?, Geophys. Res. Lett., 30(19), 1992, doi:10.1029/2003GL018126, 2003.

Fritz, C., Campbell, D. I., and Schipper, L. A.: Oscillating peat surface levels in a restiad peatland, New Zealand – magnitude and spatiotemporal variability, Hydrol. Process., doi:10.1002/hyp.6912, 2007.

Granberg, G., Grip, H., Lofvenius, M. O., Sundh, I., Svensson, B. H., and Nillson, M.: A simple model for simulation of water content, soil frost, and soil temperatures in boreal mixed mires, Water Resour. Res., 35(12), 3771–3782, 1999.

IPCC, 2001: Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp., 2001.

IPCC Third Assessment Report: Climate Change 2001 – Synthesis Report, Stand-alone edition, edited by: Watson, R. T. and the Core Writing Team, IPCC, Geneva, Switzerland, 184 pp., 2001.

Johansson, T.: Temporal and spatial variability of carbon cycling in a subarctic landscape, Ph.D., Department of Physical Geography and Ecosystem Analysis, Lund University, 2006.

Kettunen, A., Kaitala, V., Lehtinen, A., Lohila, A., Alm, J., Solvola, J., Martikainen, P. J.: CH_4 production and oxidation potentials in relation to water table fluctuations in two boreal mires, Soil Biol. Biochem., 31, 1741–1749, 1999.

King, J. Y. and Reeburg, W. S.: A pulse-labelling experiment to determine the contribution of recent plant photosynthates to net CH_4 emissions in arctic wet sedge tundra, Soil. Biol. Biochem., 34, 173–180, 2002.

Matthews, E. and Fung, I.: CH_4 emissions from natural wetlands: global distribution, area and environment characteristics of sources, Global Biogeochem. Cy., 1, 61–86, 1987.

Moore, T. R. and Knowles, R.: CH_4 emissions from fen, bog and swamp peatlands in Quebec, Biogeochemistry, 11, 45–61, 1990.

NOAA-NCDC website: http://lwf.ncdc.noaa.gov/oa/ncdc.html, last access: June 2007.

Öquist, M. G. and Svensson, B. H.: Vascular plants as regulators of CH_4 emissions from a subarctic mire ecosystem, J. Geophys. Res., 107(D21), 4580, doi:10.1029/2001JD001030, 2002.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A.G.: Soil carbon pools and world life zones, Nature, 298, 22–54, 1982.

Raghoebarsing, A. A., Smolders, A. J. P., Schmid, M. C., Rijpstra, W. I. C, Wolters-Arts, M., Derksen, J., Jetten, M. S. M., Schouten, S., Sinninghe Damsté, J. S., Lamers, L. P. M., Roelofs, J. G. M., Op den Camp, H. J. M., and Strous, M.: Methanotrophic symbionts provide C for photosynthesis in peat bogs, Nature, 436, 1153–1156, 2005.

Reay, D. (Lead Author) and Hughes, P. (Topic Editor): CH_4, in: Encyclopedia of Earth, edited by: Cutler, J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment), Published November 24, 2006 (Retrieved January 22, 2007), 2006.

Rivkina, E. M., Friedmann, E. I., McKay, K. P., and Gilichinsky, D. A.: Metabolic activity of permafrost bacteria below the freezing point, Appl. Environ. Microb., 66(8), 3230–3233, 2000.

Rosswall, T. and Heal, O. W. (Eds.): Structure and Function of Tundra Ecosystems, Ecol. Bull. (Stockholm), 20, 265–294, 1975.

Roulet, N., Moore, T., Bubier, J., and Lafleur, P.: Northern fens: CH_4 flux and climatic change, Tellus, 44B, 100–105, 1991.

Steele, L. P., Fraser, J. P., Rasmussen, R. A., Khalil, M. A. K., Conway, T. J., Crawford, A. J., Gammon, R. H., Maserie, K. A., and Thoning, K. W.: The global distribution of CH_4 in the troposphere, J. Atmos. Chem., 5, 125–172, 1987.

Solomon, S., Qin, D., Manning, M., Alley, R. B., Berntsen, T., Bindoff, N. L., Chen, Z., Chidthaisong, A., Gregory, J. M., Hegerl, G. C., Heimann, M., Hewitson, B., Hoskins, B. J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T. F., Whetton, P., Wood, R. A., and Wratt, D.: Technical Summary, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Ström, L. and Christensen, T. R.: Below ground carbon turnover and greenhouse gas exchanges in a sub-arctic wetland, Soil Biol. Biochem., 39(7), 1689–1698, 2007.

Svensson, B. H. and Rosswall, T.: In situ CH_4 production from acid peat in plant communities with different moisture regime in a subarctic mire, Oikos, 43, 341–350, 1984.

Turetsky, M. R., Wieder, R. K., and Vitt, D. H.: Boreal peatland C fluxes under varying permafrost regimes, Soil Biol. Biochem., 34, 907–912, 2002.

Van Genuchten, M. T.: A closed form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44(5), 892–898, 1980.

Van Huissteden, J., Maximov, T. C., and Dolman, A. J.: High CH_4 flux from an arctic floodplain (Indigirka lowlands, Eastern Siberia), J. Geophys. Res., 110, G02002, doi:10.1029/2005JG000010, 2005.

Van Huissteden, J., Van den Bos, M., and MartcorenaAlvarez, I.: Modelling the effect of water-table management on CO_2 and CH_4 fluxes from peat soils, Neth. J. Geosci., 85, 3–18, 2006a.

Van Huissteden, J., Maximov, T. C., and Dolman, H.: CH_4 fluxes in 2004 and 2005 in the Northeast Siberian tundra near Chokhurdagh, Indigirka Lowlands, in: International workshop on H_2O and CO_2 exchange in Siberia, edited by: Dolman, H., Moors, E., Ohta, T., Maximov, T. C., Nagoya, Japan, 33–36, 2006b.

van der Molen, M. K., van Huissteden, J., Parmentier, F. J. W., Petrescu, A. M. R., Dolman, A. J., Maximov, T. C., Kononov, A. V., Karsanaev, S. V., and Suzdalov, D. A.: The growing season greenhouse gas balance of a continental tundra site in the Indigirka lowlands, NE Siberia, Biogeosciences, 4, 985–1003, 2007, http://www.biogeosciences.net/4/985/2007/.

Wagner, D., Gattinger, A., Embacher, A., Pfeiffer, E.-M., Schloter, M., and Lipski, A.: Methanogenic activity and biomass in Holocene permafrost deposits of the Lena Delta, Siberian Arctic and its implication for the global CH_4 budget, Global Change Biol., 13, 1089–1099, doi:10.1111/j.1365-2486.2007.01331.x, 2007.

Walter, B. P., Heimann, M., Shannon, R. D., and White, J. R.: A process based model to derive CH_4 emissions from natural wetlands, Report no. 215 Max-Planck-Institut für Meteorologie (Hamburg), 21 pp., 1996.

Walter, B. P. and Heimann, M.: A process-based, climate-sensitive model to derive CH_4 emissions from natural wetlands: Application to five wetland sites, sensitivity to model parameters, and climate, Global Biogeochem. Cy., 14, 745–765, 2000.

Weiss, R., Alm, J., Laiho, R., and Laine, J.: Modeling moisture retention in peat soils, Soil Sci. Soc. Am. J., 62, 305–313, 1998.

Whalen, S. C. and Reeburgh, W. S.: Interannual variations I tundra CH_4 emissions: A four-year time series at fixed sites, Global Biogeochem. Cy., 6, 139–159, 1992.

Whiting, G. J. and Chanton, J. P.: Primary production control of CH_4 emissions from wetlands, Nature, 364, 794–795, 1993.

Yurova, A., Wolf, A., Sagerfors, J., and Nilsson, M.: Variations in net ecosystem exchange of carbon dioxide in a boreal mire: Modelling Mechanisms Linked to Water Table Position, J. Geophys. Res., Biogeosciences, 112, G02025, doi:10.1029/2006JG000342, 2007.