Biogeosciences Discuss., 9, 15853–15900, 2012
www.biogeosciences-discuss.net/9/15853/2012/
doi:10.5194/bgd-9-15853-2012

Biogeosciences Discussions

Revisiting factors controlling methane emissions from high-arctic tundra

M. Mastepanov[1], C. Sigsgaard[2], T. Tagesson[1,2], L. Ström[1], M. P. Tamstorf[3], M. Lund[1,3], and T. R. Christensen[1,4]

[1]Department of Physical Geography and Ecosystem Science, Lund University, Sweden
[2]Institute of Geography and Geology, University of Copenhagen, Denmark
[3]Arctic Research Centre, Bioscience, Aarhus University, Denmark
[4]Greenland Climate Research Centre, Nuuk, Greenland

Received: 23 October 2012 – Accepted: 6 November 2012 – Published: 13 November 2012

Correspondence to: M. Mastepanov (Mikhail.Mastepanov@nateko.lu.se)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Among the numerous studies of methane emission from northern wetlands the number of measurements carried on at high latitudes (north of the Arctic Circle) is very limited, and within these there is a bias towards studies of the growing season. Here we present results of five years of automatic chamber measurements at a high-arctic location in Zackenberg, NE Greenland covering both the growing seasons and two months of the following freeze-in period. The measurements show clear seasonal dynamics in methane emission. The start of the growing season increase in CH_4 fluxes were strongly related to the date of snow melt. The greatest variation in fluxes between the study years were observed during the first part of the growing season. Somewhat surprisingly this variability could not be explained by commonly known factors controlling methane emission, i.e. temperature and water table position. Late in the growing season CH_4 emissions were found to be very similar between the study years (except the extremely dry 2010) despite large differences in climatic factors (temperature and water table). Late-season bursts of CH_4 coinciding with soil freezing in the autumn were observed at least during three years between 2006 and 2010. The accumulated emission during the freeze-in CH_4 bursts was comparable in size with the growing season emission for the year 2007, and about one third of the growing season emissions for the years 2009 and 2010. In all three cases the CH_4 burst was accompanied by a corresponding episodic increase in CO_2 emission, which can compose a significant contribution to the annual CO_2 flux budget. The most probable mechanism of the late season CH_4 and CO_2 bursts is physical release of gases, accumulated in the soil during the growing season. In this study we investigate the drivers and links between growing season and late season fluxes. The reported surprising seasonal dynamics of CH_4 emissions at this site show that there are important occasions where conventional knowledge on factors controlling methane emissions is overruled by other processes, acting in longer than seasonal time scales. Our findings suggest the importance of multiyear studies with continued focus on shoulder seasons.

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1 Introduction

The Arctic is changing as a consequence of climate change (Christensen et al., 2004; Johansson et al., 2006; Serreze et al., 2000; Tarnocai, 2006). Somewhere within all the changes that affect snow, ice, permafrost, and vegetation distributions, a suite of changes to ecosystem biogeochemical cycling is also happening. With the effects of global warming becoming all the more evident and happening first in the Arctic, there is a special obligation to, firstly, monitor and study how the arctic environment is changing and, secondly, improve our process understanding of how these changes are affecting and feeding back to the climate system (Callaghan et al., 2011).

There are several unresolved and also recently appeared new major question marks to our basic understanding of the high northern latitudes and their greenhouse gas source strength as well as the distribution of these in time and space (McGuire et al., 2012). Our poor understanding of these questions is also reflected in our lacking capability of explaining major variations in the growth rate of atmospheric methane. After a decade of unexplained variations (down to zero) in the atmospheric growth rate of methane the data from recent years show that this is back up at a substantial rate of increase and evidence from the atmospheric data indicates that there may well be a high latitude biogenic source signature involved (E. J. Dlugokencky, personal communication, 2010). But, in general these important oscillations in atmospheric methane concentrations are poorly understood which highlights the need for long term monitoring of source variations on the ground. Here we present a study of multi-year high time-resolution observations of methane emissions from a high-arctic site.

The main aim with the study was to obtain and analyze an multi-annual dataset 2006–2010 of CH_4 fluxes in a high-arctic wet tundra ecosystem in Zackenberg, NE Greenland, covering the growing seasons from the snow melt into the period of the soil freezing. Our long time series of CH_4 emissions also allowed us to investigate the primary environmental controls on the CH_4 emissions. In addition, CO_2 fluxes were also

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measured and this allows us to assess the seasonal behavior of both gases including the CO_2/CH_4 ratio of emissions.

2 Methods

2.1 Site description

Field measurements of CH_4 and CO_2 fluxes were carried out at a fen site in Zackenberg valley, situated in the Northeast Greenland National Park (74° 30′ N, 21° 00′ W). The site is located in the High Arctic (Meltofte and Rasch, 2008), with monthly mean air temperatures below −20 °C during winter and between +3 and +7 °C during summer (Hansen et al., 2008). Between 1991 and 2005, the area experienced a significant warming of 2.25 °C (Hansen et al., 2008). The average annual precipitation was 261 mm for 1996–2005, with 90 % as snow (Hansen et al., 2008). The site was established as part of the GeoBasis part of the Greenland Ecosystem Monitoring (GEM) program in 2005. It is, however, very similar and close to, (within 50 m) of an earlier flux measurement site (Joabsson and Christensen, 2001; Ström et al., 2003), and within one km distance to the south of another former flux study site (Christensen et al., 2000; Friborg et al., 2000; Søgaard et al., 2000; Nordstrøm et al., 2001) as well as a current site making complimentary tower and experimental measurements (Tagesson et al., 2012), all in the same fen complex called *Rylekærene* (dunlin fens). The current site vegetation characteristics were dominated by *Eriophorum scheuchzeri*, *Carex subspathacea*, *Arctagrostis latifolia* and *Dupontia psilosantha*.

2.2 Measurements and calculations

Fluxes of CH_4 and CO_2 were measured using an automatic chamber technique (Goulden and Crill, 1997). Six transparent Plexiglas chambers 0.6 × 0.6 m area and 0.3 m height were installed along a transect from the fringe of the fen into the wet fen area. The distance between individual chambers was 0.3–0.6 m. Each chamber was

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equipped with a fan for ventilation and gas mixing. The chambers were connected to a stationary analytical box by couples of 25 m long High Density Polyethylene tubes (inner diameter 4 mm). Each chamber was activated for 10 min every hour; the gas from the active chamber was sucked with rate about 0.4 l min^{-1} through a non-destructive CO_2 analyzer (SBA-4, PP Systems, UK) and a likewise non-destructive CH_4 analyzer (DLT100, Los Gatos Research, USA) before returning to the chamber. The primary concentration data were recorded at 1 Hz for CH_4 and 0.625 Hz for CO_2. Active chamber fan was running all 10 min, first 3 min the chamber was ventilated open, then closed for 5 min, then opened again and ventilated for 2 min.

The chambers were installed in August 2005. Due to possible artificial effects of installations, however, the data from 2005 is not included in the current study. Due to various technical problems, the data stream each year contained more or less prolonged gaps. In 2006 measurements started before snow melt, and ended 26 August, 11 days before estimated end of growing season, which followed from the routine closing of the Zackenberg station as practiced until 2007. In 2006 the measurements had many small interruptions; moreover, only four out of six chambers were working this season (the remaining two were destroyed by muskoxen). The snow melt in 2007 was almost a month earlier than in 2006, and the measurements only commenced 14 days after snow melt. Due to the International Polar Year it was in 2007 decided to cover the shoulder seasons for Zackenberg Research Station Operations. This practice has been carried on since then keeping the station open until late October with CH_4 measurements being continued as long into the autumn as possible. During 2008 the automatic system was working well and almost without interruptions from the second day after snow melt until day of year (DOY) 238, when the instrument broke. However, for a period of DOY 283–290 another CH_4 analyzer (DLT200, Los Gatos Research, USA) was borrowed and connected to automatic chamber 1, working in its normal schedule (one measurement per hour). During 2009 the system was started one week after snow melt and worked well until DOY 193 where, due to technical problems, measurements were interrupted until DOY 224. During the gap, three campaigns of semi-manual measurements

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were performed at DOY 208, 212 and 217 (with an analyzer borrowed from a separate study). The regular measurements resumed at DOY 224 and continued until DOY 297. During 2010 the system was started one week after snow melt and worked well until DOY 306 (further extended measurement campaign). The continuity in the CO_2 and CH_4 measurements were closely linked during all five years, so the timing and source of most data gaps were the same, except for 2006, when the CO_2 analyzer broke down on DOY 219, while the CH_4 analyzer was working until DOY 238.

CH_4 and CO_2 fluxes were calculated upon the linear regression over the primary concentration data (for the detailed description of calculation methods, see Mastepanov et al., 2012) using air temperature and pressure data collected at a meteorological station (ClimateBasis, 2010; Hansen et al., 2008) about 700 m from the site. In case of ebullition different calculation methods were used, based of bubbles frequency and mean CH_4 and CO_2 content.

For diurnal dynamic analysis within a specified time interval (Fig. 6) the individual fluxes from each chamber were normalized to average flux for this chamber and this period, then detrended (dividing each normalized value by its linear trend approximation).

For an interannual comparison of the environmental parameters and flux values, most of which had gaps in the data or slightly different ways of being measured, a ranking was used. We used either integration of regular gapless measurements (air and soil temperatures) or a visual integration for irregular measurements (water table level, active layer thickness) and data with gaps (CH_4 and CO_2 fluxes). The ranking was done between years within three 30-days intervals. Highest values were represented as rank 1, followed by rank 2, etc. When the difference between two or more years was much smaller than between others, their rank was considered the same.

Apart from CO_2 and CH_4, ambient PAR level was measured at 10 Hz and recorded as 1 Hz averages using one sensor (LI-190SA, LiCor, USA) installed outside the chambers. The soil temperatures at 5, 10 and 15 cm depths were recorded near the middle of chamber transect by loggers (Tinytag Plus, Gemini Data Loggers, UK), every 5 min

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during June–October and every one hour during the rest of the year. Water table depth and active layer thickness were measured manually every one-two weeks in the snow-free season. In 2006 water table and active layer were measured in a single representative location at the site, relative to the surface of mosses. In 2007 the reference one-meter metal stick was hammered down to the permafrost, then the surface, water table and active layer levels were measured relative to the stick zero mark (which was at the moss surface level when installed), in 6 locations in front of each chamber. Once per year this zero mark was checked by differential GPS.

2.3 Timescale definitions

For the data treatment and representation we used the following timescale definitions:

Day of year (DOY): wide used time scale representation relative to the start of calendar year. In our calculations 1 January was DOY 1 and 2 January was DOY 2, etc. in integer representation. In fractional representation 1 January 6:00 was DOY 1.25 and 1 January 18:00 was DOY 1.75, etc.

Day of snowmelt (DSM): the date, or day of year (DOY) when the snow cover in the chambers and around the chambers disappeared. In some years DSM can have ±1 day precision due to arbitrary determination.

Day after snowmelt (DASM): suggested time scale representation relative to the start of the growing season. In our calculations DSM was DASM 0, the next day was DASM 1, etc. in integer representation. In fractional representation 6:00 of DSM was DASM 0.25, even if the moment defined as the complete snow melt was later this day.

Growing season: defined as the interval between DSM and the date when soil at 5 cm depth reached 0 °C again.

Zero curtain: time interval clearly visible in soil temperature records when the temperature stays close to zero (because of water–ice phase change) – in our case defined between the first day after the growing season, and the date when the soil temperature at 5 cm started to fall below zero, with < 1 °C precision.

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Freezing period: the interval between zero curtain and when the entire active layer is frozen. Due to closure of the station our measurements never continued until the end of the freezing period since that occurs later during the winter.

Post-season period: the interval from the start of zero curtain to the end of the measurement campaign.

3 Results

3.1 Environmental conditions

A summary of air temperature and key dates related to the temperature regimes for the years 2006–2010 is presented in Table 1. The growing seasons for the different years were very different with respect to the start and end dates, as well as in the zero curtain timing and length. The maximum variation between snowmelt dates reached 34 days between the earliest (2009) and the latest (2006) during the study years. Consequently, the duration of the growing season in 2009 was about 1/3 longer than in 2006. However, the growing season ending date did also vary up to 19 days (between 2006 and 2008).

The monthly average air temperatures for June, July and August were in most cases higher than for the previous ten-year period, except for a colder June in 2006 and 2009 and July in 2010. The warmest year of the five was 2008, both for the three summer months individually, altogether and for growing season average. The nominally coldest for JJA average temperature was 2006, however 2009 had lower growing season average (Table 1).

The soil temperature records at the site were started in late June 2007. The subsequent dynamics are shown in Fig. 1, both on DOY and DASM scale. For interannual comparison of soil temperatures ranking was used (Table 2); for the first and second 30 days of the growing season 2008 was warmest, for the third 30 days 2009 was warmer. In the end of the growing seasons, the temperatures at all 3 depths came to 0 °C, and then stayed almost constant for 2–3 weeks (i.e. the zero curtain, see Table 1).

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The zero curtain periods had practically the same duration in four out of five years, except almost 60 % longer in 2009 because of unusually early and deep snow cover, insulating the soil. The following freezing of the active layer was also slower in 2009.

The water table dynamics in 2006–2010 are shown in Fig. 2 with ranks in Table 2. After snow melt, the water table was above the surface (here defined as the average surface of moss layer) in 2006–2007, and close to the surface in 2008–2010. We have no measurements of water movement, but we could visually observe that the water regime at the site changed between 2007 and 2008 seasons. Surface water was moving slowly in 2006–2007, but much faster in 2008–2010. During the growing season the water table was generally decreasing (Fig. 2), however large variations due to precipitation were observed. In 2010 water table was lower than any other year during the whole growing season.

The dynamics of active layer thickness (the distance between the moss surface and the table of the frozen layer) is shown in Fig. 3a, b. The soil started to thaw about the date of snowmelt; however, the initial rate of thawing was different in different years. The maximum active layer thickness was found in 2009 (Fig. 3a, b), however, the measurements of the freezing front relative to the fix point (Fig. 3c) showed that the permafrost table was moving deeper every year during 2006–2009, but the surface was also lowered. In 2010, the permafrost table did not change, but the active layer became significantly thinner to the end of the growing season because of the lowering surface.

3.2 CH_4 fluxes

The dynamics of CH_4 fluxes for 2006–2010 are shown in Fig. 4 with the main numbers included in Table 1. In 2006 we observed CH_4 fluxes starting a few days after snow melt and exponentially increasing until DASM 21. Then the fluxes stabilized for about a week, and started to gradually decrease.

During 2007, the first week of measurements gave results very similar to 2006 (in DASM timescale, Fig. 4b), then the flux continued to rise above 2006 level, and only about DASM 30 started to decline. It gradually decreased during the rest of

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growing season and through the zero curtain. Quite unexpectedly, after the zero curtain, the fluxes started to increase again and peaked with extremely high values up to 112.5 mg CH_4 m^{-2} h^{-1} (Mastepanov et al., 2008). The maximum of this late-season emission peak was observed around DOY 280, however, the measurements did not continue long enough to document the end of the peak allowing only a partial estimate of the total amount of emitted methane. The registered amount of CH_4 emitted during post-season 2007 was 3.76 g C m^{-2}, or about 92 % of the estimated growing season emission (Table 1).

During 2008, CH_4 emission were extremely low until DASM 17 (Fig. 4), then started to slowly rise until DASM 45–49, when it more or less reached the level of the same relative period in 2006 and 2007. Then the emission declined like in 2007. The measurements during the freeze in period (DOY 283–290) showed very low fluxes (Fig. 4a) with no evidence of the late-season peak.

During 2009 the rate of CH_4 emission increased during the first 30 days of growing season and was intermediate between 2008 and 2006–2007; then the fluxes started to decrease and came in level with the preceding years. The first signs of late-season emission peak were registered at DOY 263, however, the following fluxes were not as high as in 2007. Only three days of very high fluxes (up to 99 mg CH_4 m^{-2} h^{-1}) were registered in one of the chambers at DOY 293–295, while the average post-season flux for all 6 chambers was 0.92 mg CH_4 m^{-2} h^{-1}(Table 1), more than 4 times less than in 2007.

In the beginning of the growing season of 2010, CH_4 fluxes were growing fast, then stopped around DASM 20 and thereafter gradually decreased. Thus the maximum of the emission peak was higher and earlier than in 2008 and 2009 (Fig. 4b), although lower and earlier than in 2006 and 2007. The emission rates in the second half of the growing season 2010 were significantly lower than in 2006–2009. During the freezing season 2010 a limited but significant increase in CH_4 emission was detected (Fig. 4a). The average post-season flux was 0.55 mg CH_4 m^{-2} h^{-1}, with the total registered amount equaling 30 % of the growing season CH_4 (Table 1).

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3.3 CO_2 fluxes

The dynamics of CO_2 fluxes for 2006–2010 is shown in Fig. 5 with the main numbers included in Table 1. The growing season CO_2 fluxes (NEE) were more erratic than CH_4 emissions. At the start of the season i.e. the first 7–12 days after snow melt, the ecosystem was a small atmospheric source of CO_2. After that CO_2 fixation started to prevail. During the first 30 days of the growing season the most pronounced net carbon uptake was registered in 2007 and 2008, with the 2008 uptake lasting longer and with the greater strength (daily average of $-211\,mg\,C\,m^{-2}\,h^{-1}$), while in 2007 the uptake was shorter and weaker. After the peak, the ecosystem production started to decrease, and NEE crossed zero around DOY 230–240. The first 30 days of the growing season in 2009 were significantly less productive (lowest daily average NEE of $-66\,mg\,C\,m^{-2}\,h^{-1}$), with the later seasonal dynamics being uncertain due to measurement gaps. The productivity during the first 30 days of growing season 2006 were somewhere between 2007–2008 and 2009 with the later seasonal dynamics in 2006 being somewhat uncertain. In 2010 CO_2 fluxes were close to 2007–2008 during DASM 20–30 but then changed to less fixation and even net emission.

In the post-season 2007 (starting from DOY 263) a CO_2 emission peak was observed; the highest flux values reached $3\,g\,CO_2\,m^{-2}\,h^{-1}$, while the average for all registered post-season CO_2 fluxes was about $400\,mg\,CO_2\,m^{-2}\,h^{-1}$ (Table 1). As for CH_4, the CO_2 measurements also did not continue long enough to capture the end of the peak and measure the whole amount of emitted CO_2. The registered amount of CO_2 emitted during post-season 2007 was $130\,g\,C\,m^{-2}$, almost two times more than was fixed during the growing season (Table 1). In the late season 2009 only moderate fluxes were observed; the highest flux value reaching $242\,mg\,CO_2\,m^{-2}\,h^{-1}$, while the average for all registered post-season CO_2 fluxes was about $150\,mg\,CO_2\,m^{-2}\,h^{-1}$. The registered amount of CO_2 emitted during post-season 2009 was $8.9\,g\,C\,m^{-2}$, or about a quarter of the carbon, fixed during the growing season (Table 1). In the post-season 2010 a strong CO_2 emission was observed. The highest flux values were more than

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$10\,g\,CO_2\,m^{-2}\,h^{-1}$, while the average for all registered post-season CO_2 fluxes was about $340\,mg\,CO_2\,m^{-2}\,h^{-1}$ (Table 1). The registered amount of CO_2 emitted during post-season 2010 was almost $100\,g\,C\,m^{-2}$, or almost three times more than was fixed during the growing season.

3.4 Ebullition

All the fluxes described above are so called steady fluxes (Ström et al., 2005). The signs of ebullition were observed in the order of 10 per month per chamber, but most of them were probably not real ebullition events. The typical amounts of CH_4 and CO_2, released by a single bubble, were in the order of 0.1 mg of CH_4 and 1 mg of CO_2, correspondingly. The estimated seasonal ebullitional release of both CH_4 and CO_2 were within 0.1–1 % of the total seasonal flux. As this value appeared to be within the uncertainty in the steady fluxes, the ebullition events were neglected in all the following calculations.

4 Discussion

4.1 Growing season

4.1.1 Environmental variables

In the literature, there are different ways to define the growing season depending on the focus of study (e.g. Grøndahl et al., 2007, 2008; Jackowicz-Korczynski et al., 2010). In this study we need a proxy that would help to compare the different years, highlighting the similarities and the differences between them. The most straight-forward, calendar-based proxy does not work for an ecosystem, where snowmelt, thawing of the soil, vegetation development, as well as CH_4 and CO_2 fluxes may be shifted more than a month at the beginning of the season (see Table 1 and Figs. 1, 3, 4, 5). However,

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taking the snow melt date as the starting point of the growing season (Grøndahl et al., 2007), proved a useful unifying concept for the majority of environmental factors and for CH_4 and CO_2 fluxes. Not only is snow melt itself important, but it is also starting a strong energy flux into the soil and melting of the soil. In Zackenberg snow thaws rapidly, and the date when the upper 5–10 cm of the soil reach positive temperatures is within 1–2 days from the date of visual snow melt, both in dry and wet sub-habitats. In this context it does not really matter, whether we define day zero as the first snow-free day or as the first day when the soil temperature at 5–10 cm went above zero. As we have longer visual records of snow melt at our site, we have chosen the first.

As our main focus in this study was in CH_4 fluxes, and the most intriguing finding was the late-season CH_4 burst during gradual freezing of active layer (Mastepanov et al., 2008), we chose the soil temperature as the main proxy for the end of growing season. At DOY 250–270 (Fig. 1) the soil temperature at 5, 10 and 15 cm came to zero almost synchronously, and then kept at zero for a long period called zero curtain. During this period the free water in the soil profile is gradually turned to ice, and during this period in 2007, 2009 and 2010 the increase in CH_4 fluxes started. When the soil temperature at any sensor fell below zero, we concluded that all free water at this layer was frozen and the frozen front was gradually moving down. We used the time it took the freezing front to move from 5 to 15 cm depth as a proxy of the freezing speed (Table 1).

Snow is one of the main controlling factors for the beginning of the growing season (Grøndahl et al., 2008). A greater amount of snow, causing a later snow melt also leads to a larger amount of water afterwards. Indeed, after a very late snow melt in 2006 the water at the site was standing high for the subsequent 30 days; in 2007 the snow melted much earlier, and the water table dropped faster (Fig. 2). However, this situation was different in 2008–2010: during the first 30 days the water table stayed constantly near the surface, regardless a very different snow melt date and precipitation pattern (not shown). This may be an indication of a changed water regime, from more stagnant system in 2006–2007 to a more running one in 2008–2010. After the DASM 30 the

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water table dynamics were very variable in the five years and in this latter part of the season mainly reflecting variations in the precipitation pattern.

The dynamics of the active layer is an important factor both for seasonal and for interannual subsurface processes. The majority of CH_4 and CO_2 emitted at the surface originate from processes, taking place in unfrozen soil. Both CO_2 and CH_4 production at temperatures below zero have been documented (e.g. Rivkina et al., 2000; Panikov et al., 2006) but their magnitude is dismissible compared with above-zero degree production rates. If permafrost melting is taking place, new layers are included in the active turnover every year, which can have significant effects on the ecosystem's carbon budget in a setting where the permafrost is organic-reach (e.g. Zimov et al., 2006; Schuur et al., 2009). Lowering of the permafrost table is not equal to increasing of active layer thickness in case of the surface settlement (Tarnocai et al., 2004). Since installing a permanent reference point in 2007 we observed vertical movements of the soil and moss surface both at seasonal and multiyear time scale. Within a season these movements were probably caused by water level (at high water peat and vegetation have negative weight and slightly expand upwards, while at low water the matrix collapses slightly) and freezing-melting (water-filled matrix expands when freezing and collapses when melting). Thus, towards the end of the growing season 2007 the surface level was 6–7 cm lower, than in the beginning of the growing season – most likely both because of very low water table and gradual ground thaw throughout the season. Similar dynamics were observed in the following years, more or less expressed depending on the water table dynamics.

The surface level was lowering over the years of study, regardless of the water table and thaw depth dynamics. The surface in the beginning of 2010 season was 10–15 cm lower than in the beginning of 2007 season. While the maximum active layer thickness increased about 7 cm over the three years, the real permafrost melt was about 17 cm (Fig. 3a, d).

The gradual permafrost melting was observed during 2006–2009, but the upper permafrost bound did not significantly change between 2009 and 2010 (Fig. 3c). The

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explanation may be the unusual drought in the 2010 growing season, where possibly drying of the peat reduced its thermal conductivity and thus melting of the ground beneath.

4.1.2 CH_4 fluxes

During the five study years, the accumulated growing season CH_4 flux was highly variable in the DOY timescale (Fig. 4a) but with some striking synchronous temporal dynamics at the DASM scale (Fig. 4b). The early onset of the growing season emission was synchronized by snow melt and soil thaw (Fig. 3). However, during the second week the rising flux rates started to differ. The main difference in the flux rates between the different seasons was observed during the first 30–40 days after snow melt, and after this point in time the flux curves for 2006–2009 gathered towards almost identical mean values. During 2010, CH_4 emission had the same pattern, but the level of emissions in the second half of the growing season was lower than in previous years. In relation to this distinct flux pattern we will in the following discuss the parameters most well known from the literature to be controlling methane emissions from wetlands.

The most recognized factors affecting CH_4 efflux in wetlands are the temperature and the water table (e.g. Bubier et al., 1993; Dise et al., 1993; Christensen et al., 2003; Pelletier et al., 2007; Elberling et al., 2008; Glaser and Chanton, 2009). The main temperature effect is an exponential increase of methanogenic activity with soil temperature at the given active depth. In our study, the temperatures during the first part of the growing season could not explain the differences in CH_4 emissions between years. The warmest first 30 days of the growing season were in 2008 (Table 1, Table 2), while CH_4 fluxes were the lowest within five years (Table 2, Fig. 4). The highest CH_4 emission peak was in 2007 (Fig. 4), year with mild air temperature during first 30 days of growing season. All other ways of handling air temperature (averages for June and July separately, JJA overall, etc. – see Table 1) also did not show any immediate correlation with the differences in observed methane emissions. Air temperature variations in the last part of the growing seasons (remembering the seasons were shifted in calendar

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time) were also quite large between the years while the CH_4 fluxes showed very similar values, except 2010. For this period no correlations between CH_4 fluxes and air temperatures were found. Air temperature has mainly indirect effect on the processes involved in methane emission, however, it is widely used for models, flux interpolations and upscaling, because air temperature data is easier to obtain than proper soil temperature data. In the case of the Zackenberg fen presented here such temperature based models will not work.

Soil temperature data (Fig. 1, Table 2) is also not in line with interannual variability of CH_4 fluxes. Soil temperatures during first 30 days of season were higher in 2008 than in 2009 while in terms of the methane fluxes the opposite was the case. The next 30 days temperatures were significantly different, while the fluxes were approaching each other. For the last part of the growing season the fluxes in 2007 and 2009 (and, probably, in 2008) were almost identical, while soil temperature at 10–15 cm was about twice as high in 2009 compared with 2007 and 2008.

Within individual years, correlations between soil temperatures and CH_4 flux can be found (Table 3), both by linear and exponential approximation. At the first view, this corresponds with similar findings at a variety of scales ranging from laboratory studies (Svensson and Roswall, 1984) to multi-year and site studies (Christensen et al., 2003). However, this simple correlation does not work for more than one season in our case. For example, linear correlation between soil temperature and CH_4 flux has very high R^2 values of 0.86, 0.82 and 0.92 for 2007, 2009 and 2010, respectively, but the slopes of these are very different (Table 3). The same applies to exponential correlations. Most probably, highly pronounced seasonality both in soil temperatures and CH_4 fluxes is typical for this arctic environment with its short summer, and this causes statistical correlation between them within each season. However this correlation may not be applicable to other years.

Comparable multi-year studies in a temperate fen (Sallie's Fen, NH, USA, 43° N – Treat et al., 2007) and a temperate bog (Mer Bleue Bog, ON, Canada, 45° N – Moore et al., 2011) also report good correlation of CH_4 fluxes with temperature within

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individual years and weak correlation for 5 yr combined. Among many differences between the three sites, the most remarkable may be the distinction in the seasonal CH_4 flux pattern. At Sallie's Fen the fluxes slowly increase throughout a season, peaking in August, which coincides with highest seasonal temperatures. At Mer Bleue Bog the pattern was similar, but as the measurements were continued longer into autumn (May–November) than at Sallie's Fen (May–August), the seasonal correlation of CH_4 fluxes with temperature was affected by variations in autumn fluxes. In our study the peak of CH_4 fluxes was usually closer to the beginning of the season, about DASM 20–30 (Fig. 4b), which may or may not coincide with warmest part of the season (Fig. 1). Those peaks, carrying most of the seasonal emission and most of interannual flux variation, seem to be a feature of high-latitude ecosystem.

The process of methanogenesis (as well as methanotrophic oxidation) is a metabolic activity and definitely temperature dependent. So there is no way that methane production may be detached from being affected by soil temperature. However, the interannual variability, found in this study, cannot be explained by temperature, which should mean that not production itself, but some other processes play an overriding role in controlling the net emission.

Another widely used predictor for CH_4 emission is the water table position (e.g. Dise et al., 1993; Daulat and Clymo, 1998; Hargreaves and Fowler, 1998; Friborg et al., 2000; Elberling et al., 2008). In our study water table dynamics was also very different from the methane flux dynamics, and we failed to find any reasonable correlation between them, except the year 2010 (Table 3). For the first 30 days of the growing season (Fig. 2, Table 2) water table was highest in 2006 (second large CH_4 emission) and lowest in 2010 (third large CH_4 emission). Comparing the two-year intervals 2006–2007 (high water table, high CH_4 emission) and 2008–2009 (lower water table, lower emission) may look promising. However, within the two-year intervals this logic does not work. The flux in 2007 was higher than in 2006 at DASM 20–40, when the water table was much lower. The flux in 2009 was about twice as high as in 2008, while water table was almost the same. At DASM 30–60 water table was above the surface

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in 2006, slightly below the surface in 2008, and far below the surface in 2007 and 2009. This distribution was not reflected in CH_4 fluxes (although a little higher fluxes in 2006 could be suggested explained by a possible suppressed methanotrophic activity). Fluxes at DASM 30–60 2008 were virtually the same as in 2007 and 2009, while water table level differed dramatically. The same situation continued for the reminder of the growing season.

The lack of water table effect on CH_4 fluxes during the beginning of the growing season may be explained by the fact that despite the difference in water table it was in all years above or at the surface, which is in some sense making the conditions the same for methanogenic versus methanotrophic activity distribution. Thus, the variability of CH_4 fluxes during the first part of the season may not be caused by water table position, but at least does not contradict the notion that water table should affect the net emissions. What could be more in contrast with the conventional picture of the water table role for methane processes, is the lack of any significant correlation between water table position and fluxes in the second half of the season. Here it can be relatively low, and CH_4 fluxes the opposite when comparing the years, as well as there is a lack of any significant reaction on water table changes by CH_4 fluxes within each year. The fluxes seem to stay on their pattern regardless of even dramatic changes in the water table. A possible explanation could be that the open water table measurements in a hole are not the same as the level of 100 % water saturation in the peat matrix. Due to capillary effect, water can stay higher than we measured. However, during dry parts of the growing seasons in 2007 and 2009 the mosses and surface peat was visually clearly dry, so there was certainly an increased aerobic horizon that by conventional wisdom should stimulate methanotrophic activity. In short, it appears as if the net emissions are largely independent of the water table and this may be explained by the water table fluctuations being all (or most of them) above a certain threshold beyond which the water table no longer is a major controlling factor. It has been shown before that the water table act in a non-linear way and rather as an on-off switch in relation to the net CH_4 fluxes (Christensen et al., 2003). It seems that we at this site have the CH_4

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emissions turned on and therefore acting most years independent of the water table fluctuations.

However, in 2010 the water table dynamics were exceptional. Started from the surface at snowmelt, it started to decrease already at DASM 18, and was going down consistently for more than 60 days (Fig. 2b). This unusual drought was the most probable reason for the unusual CH_4 flux dynamics (Fig. 4b): net emission started to decrease after DASM 20 (earlier than in 2006–2009), and came to much lower values at DASM 60–90 than in previous years. We may hypothesize, that water table level is not a limiting factor for CH_4 emission at our site while it is above 20 cm depth, as in 2006–2009, but become such if it falls deeper, as it did in 2010.

Strong interannual variations in water table level were also reported for Sallie's Fen (Treat et al., 2007), where the usual trend was decreasing of water table level throughout a measurement season (May–August), while the CH_4 fluxes were increasing. This gave rise to a negative correlation within individual seasons, and no significant correlation interannually (Treat et al., 2007). In our study the seasonal trend in water table was similar, but the seasonal pattern in CH_4 fluxes was quite different, as discussed above. This led to positive correlation between water table and CH_4 emission within individual seasons. Most likely, in both studies these correlations were coincidental and water table was not the main factor affecting CH_4 fluxes. At Mer Bleue Bog (Moore et al., 2011) seasonality was slightly different, with relatively high water table during the spring, falling during the summer and rising again during the autumn. There variations of water table had a higher amplitude, and were positively correlated with CH_4 fluxes at the seasonal scale.

Further details in the CH_4 flux data points at an element of seasonal variation in the main controls: the diurnal dynamics, strongly pronounced in some periods, but absent in others (Fig. 6). At the start of the season all the chambers showed more or less pronounced diurnal dynamics with relatively lower fluxes during day time and higher during the night (note that Fig. 6 shows detrended data). These dynamics correlate well with the soil temperatures. During the peak of the growing season, the fluxes had almost

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no diurnal dynamics, while the temperature cycle was still well expressed. At the end of the season (Fig. 6c) very sharp and consistent diurnal dynamics appeared again and was consistent for more than two weeks. At this time the emission peaked during the morning hours (08:00–09:00 a.m.), which is out of phase with soil temperatures at 5–15 cm depth. Diurnal variation in CH_4 fluxes is site specific as it both have been documented present (Hargreaves and Fowler, 1998; Shannon et al., 1996; Kim et al., 1999) and not present (Rinne et al., 2007; Kormann et al., 2001; Jackovitz-Korchynski et al., 2010) in data from growing season measurements at other sites. We can hypothesize, that in our case the prevailing mechanisms in control of CH_4 emission may vary through the season, and those different mechanisms may be differently affected by soil temperature and other factors (Kim et al., 1999).

We suggest that methanotrophic activity (here we mean oxidation in the methanotrophic layer, unlike rhizospheric oxidation) during normal 2006–2009 years was also not a key factor, controlling CH_4 flux in our study. According to the classical scheme (e.g. Joabsson et al., 1999; Glaser and Chanton, 2009; Lai, 2009) methane is produced in anaerobic layer, may be to some extent stored in the soil (mainly as entrapped bubbles), transported to the surface, partly passed through the methanotrophic filter and the remaining is emitted to atmosphere. There are three main mechanisms of methane transport through the soil (e.g. Glaser and Chanton, 2009; Lai, 2009): molecular diffusion, plant-mediated transport and ebullition. In our study the ebullition was estimated to have a negligible share and due to physical reasons molecular diffusion also can not provide any high rates of emission (Christensen et al., 2003). This means plant-mediated (vascular) transport remains the main mechanism to work with in this case. By definition, it should be controlled by quantity, quality and activity of vascular plants. Unfortunately, any detailed analysis of the vegetative cover was not yet carried out in the automatic chambers (which is part of a long term monitoring program and therefore should stay untouched from destructive harvests etc). However, the CO_2 exchange can be used as an indirect proxy of the activity of the plants.

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4.1.3 CO_2 fluxes

In this study CH_4 fluxes were the main focus, and the measurements of CO_2 were complimentary. For this reason the chambers were not designed to provide both light (various levels of it) and dark measurements, as is the usual praxis for CO_2 studies using the same technique (e.g. Joabsson and Christensen, 2001). The chambers were made of transparent Plexiglas, connected by aluminum 3–5 cm wide corners. So the CO_2 measurements may be defined as light measurements, although the PAR level inside the chambers was about 20 % lower than ambient. This is a known artifact of the chamber method and in this study we did not attempt to correct it. Because of the high latitude, the real darkness did not occur until the end of July, so no dark respiration measurements were taken during the central part of the growing season. For this reason we did not try to estimate respiration and GPP separately. However, our net CO_2 fluxes throughout the season, happened to be very close to the fluxes reported earlier using combined data from eddy covariance and manual chamber methods (Nordstrøm et al., 2001), and we assume the estimations of GPP and respiration shown in this publication can be valid also for our study. Figure 7 shows a direct comparison of CO_2 fluxes from tower measurements of 1997, obtained in the same valley within 1 km distance from our site (Nordstrøm et al., 2001) and our data of 2008. The reason for comparing these particular seasons 1997 and 2008 is that they are quite comparable in the snow melt date: DOY 168–171 for the tower footprint in 1997 (Nordstrøm et al., 2001), and DOY 173 for our site in 2008. The CO_2 fluxes also show similarity both in seasonal dynamics and magnitudes (Fig. 7). One noticeable difference between these two datasets is that the positive flux peak in the beginning of the season 1997, presumably caused by physical release of stored CO_2 (Nordstrøm et al., 2001), in our measurements was significantly shorter and lower in magnitude.

NEE dynamics during the start of the season was found to be affected by date of snow melt (Fig. 5), while the drivers controlling the decay of the production towards the end of the growing season probably have a more mixed nature. The PAR level,

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important for plants productivity, decays with sunlight angle (DOY timeline). The temperature is another important factor both for the respiration and CO_2 fixation; the decrease in temperature at the end of the season correlate roughly with the calendar date (DOY), but progress differently in different years. In our dataset (Fig. 5) two out of five years had no NEE data for the end of growing season, and the data from 2007 does not show any clear pattern during this period because of weather (unstable PAR). The fluxes from 2008 and 2010 are very different between DASM 30–60, but both reach the compensation point about DASM 60. However, 2008 and 2010 datasets cannot be directly compared in terms of CO_2 exchange because of an extreme drought in 2010, so the question whether we should look for synchronism of CO_2 fluxes in the end of growing season in DOY or DASM timescales is open.

The most complete NEE dataset was obtained for the first 30–40 DASM. The initial period of positive net flux was significantly shorter and had lower magnitude than was reported in the earlier study (Nordstrøm et al., 2001). Then efflux turned to negative (net CO_2 fixation), with the highest rate in 2008 and lowest in 2009 (Table 2). Surprisingly, this did not correspond with the rates of CH_4 flux development (Fig. 4). The peaks in NEE (uptake) tend to be synchronous with the peaks in CH_4 emissions, however their magnitude did not correspond: biggest NEE peak in 2008 coincided with the smallest CH_4 peak, while the second productive 2007 had the highest CH_4 peak. The ranks of average CH_4 and CO_2 fluxes per growing season (Table 1) also do not match.

4.2 Zero curtain and freezing season

4.2.1 Environmental conditions

During the period of zero curtain the soil temperature stays almost constant at 0 °C and the main proportion of water in the soil turns to ice. Depending on the weather the freezing may take shorter or longer time. In our study (Table 1) it took 15 days in 2010, 16 days in 2008, 17 days in 2006 and 2007, and 27 days in 2009, where in the latter case unusually high snow precipitation caused high and early snow cover, insulating

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the soil. The following freeze-in rates were different between years – freezing of 5–15 cm took only 9 days in 2008, 13–14 days in 2007 and 2010, and 20 days in 2009. We assume, that the snow cover was the main factor slowing down the heat exchange in 2009. On the contrary, in 2008, high amounts of rain occurred just before the freeze-in, and subsequently the water-saturated soil was acting as a good conductor for heat flux. The high water level in the end of season 2008 turned to ice layer on the soil, which probably lowered CH_4 and CO_2 emissions.

4.2.2 Post-season CH_4 fluxes

High CH_4 fluxes in October 2007 (Fig. 4a) were coinciding with soil freezing (Fig. 1), which made us hypothesize that frost action is the main driving force for this effect (Mastepanov et al., 2008). During the growing season a significant amount of CH_4 remains in the soil profile in form of entrapped gas bubbles (e.g. Tokida et al., 2005; Mastepanov and Christensen, 2009; Glaser and Chanton, 2009). In continuous permafrost areas, where the active layer is not too deep (in our case 50–60 cm), freezing of the soil from the surface creates high pressure between the growing frost front and the permafrost bottom. This may cause gas bubbles to be squeezed out through microcracks or remaining vascular plant tissues (Fig. 8). As the pressure grows, the gas seepage follows, but when the frozen layer reaches some thickness the number of possible channels for emission decreases. Most likely some amount of bubbles remain trapped in the frozen soil.

Another possible mechanism explaining the freeze-in burst could be deactivation of methanotrophic activity when the top soil layer is frozen. According to this hypothesis, methane production is continued in deeper layers, and with deactivation of the methanotrophic filter a higher share of methane produced reaches the atmosphere. This effect may also take place, but it can only provide a tiny fraction of the huge fluxes we see. According to the mentioned biological mechanism, the permafrost bottom does not play any role and post-season fluxes should be a common case for every freezing wetland. However, many studies in lower latitudes show late-season decline of CH_4 fluxes

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without any significant peak (e.g. Jackowicz-Korczynski et al., 2010). So the biological mechanism alone does not explain CH_4 transport to the atmosphere, if the surface is frozen. It does not either explain the very high emission rates and highly stochastic flux patterns. If the source for the emission is instantly produced CH_4, the flux should be stable in time but instead we see change in orders of magnitude within a few hours. Finally, our study did not show a strongly marked CH_4 flux regulation by methanotrophic activity in the upper horizons. So we continue to keep the physical mechanism as a working hypothesis.

At this point in time we cannot clearly determine, if the autumn burst is an usual, regular or rare phenomenon. We have definitely observed it in 2007 and 2010, and in both cases the emission started to increase with freezing of upper soil horizons, came to its maximum values around time when the frozen front was down at 15 cm, and then decayed (Figs. 1, 4). We have probably seen a start of this burst in 2009 (we assume, that slower soil freezing delayed the CH_4 burst and smoothened the flux dynamics) before the station was closed for the season. We have no data for the freezing period of 2006. In 2008 the burst was not registered when it was expected to happen; perhaps we missed it because of large gaps in the data, but most probably the ice shield on the surface and fast freeze-in prevented the emission. Regardless it seems likely that the high autumn burst does not happen every year, but has some natural regularity.

4.2.3 Post-season CO_2 fluxes

In all three years, 2007, 2009 and 2010, the autumn CH_4 peak was accompanied by a corresponding CO_2 peak (Fig. 5a). This fact does not fit with the biological hypothesis for the reduction in methanotrophy being the reason alone for increasing emissions. But, it agrees with the idea of a physical process at play (Fig. 8). As the entrapped gas bubbles contain a high amount of CO_2 as well as CH_4, according to the physical hypothesis they should be emitted together. Indeed, close-up flux dynamics at freezing time (Fig. 9) shows that every single peak of CH_4 is accompanied by a simultaneous peak of CO_2. The CH_4/CO_2 ratio is almost constant for each peak, confirming the gas

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having a single origin (one entrapped bubble). Such a bubble does not exhaust instantly, like it happens at ebullition but the exhaust of one bubble takes a few hours. This confirms the idea that the gas is squeezed through very thin channels, probably the remnants of vascular plant tissues. However, the CH_4/CO_2 ratio is changing between different peaks (bubbles), starting from relative CH_4-rich in the beginning of the autumn burst towards being more CO_2-rich in the end. This pattern can also be explained by a physical theory. In the beginning of freezing the layer between permafrost and frozen soil surface contain a large amount of water. At high pressure CO_2 solubility dramatically increases, and most of the pressurized CO_2 goes to solution in un-frozen water. The solubility of CH_4 is much lower even at high pressures, and its fraction in the bubbles remains high. Forced by high pressure, these bubbles leave the soil and the overall amount of CH_4 in the system declines. When the frost propagates, liquid water becomes ice, but the dissolved gases, now with larger fraction of CO_2, remain in the solution. The CO_2 concentration in the solution rises and so does its fraction in the remaining (or new) bubbles. CH_4 is also migrating from the solution to the bubbles, but as its concentration in the solution was much smaller, the bubbles turn from CH_4-dominated to CO_2-dominated with time. The plot of CO_2 versus CH_4 ratio (Fig. 10) shows interchange of those processes for the 2007 and 2010 fluxes.

4.3 Freezing season affecting the next growing season

If the subsurface methane pool can be significantly depleted after a growing season, it may be suggested that in the beginning of the next growing season a significant part of methane production will go to refill the sub-surface pool instead of becoming emission to the atmosphere. Therefore, after a high autumn burst low CH_4 fluxes can be expected in the first part of the following season which is what our limited data from four years are showing. We have, however, still not enough data to confirm or disprove this hypothesis, but with some stretch it can explain the interchange of seasons with higher and lower CH_4 fluxes (Fig. 4). Let us assume that there were no strong CH_4 burst in the end of 2005, 2006 and 2008, and at the start of 2006 the subsurface CH_4

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pool was partly charged. Then a high fraction of the CH_4 produced was emitted (giving quite high flux in 2006), and another part stayed in the soil, charging the storage pool even more. In 2007, when this pool was even more charged, a higher emission was detected. In the autumn of 2007 the strong burst occurred, and the subsurface CH_4 pool discharged. Then in the beginning of the growing season 2008 the emission was very low because of almost all the production went to recharge the pool. To the beginning of 2009 season the pool was partially charged again, and a higher amount of CH_4 went to emission – as evident from the first part of 2009 was showing higher emission than in 2008. As the autumn discharge in 2009 was relative small, it did not overcome the recharge during the growing season, so the pool increased between 2009 and 2010 and peak emission 2010 was higher than 2009. This theory is illustrated in Fig. 11. The red bars, symbolizing the subsurface storage pool of CH_4, are sized proportionally to the emission peak maximum values for corresponding year (Table 1), which of course is not entirely correct proxy for the storage. The blue arrows, symbolizing the discharge of the storage pool due to freezing time burst, are sized proportionally to the total post-season CH_4 loss, documented in our measurements (Table 1), which is also not entirely correct because this number does include the declining background emission during zero curtain and freezing season, and does not include the missed late part of freezing season emission. However, even this schematic figure can illustrate a speculation that a single strong autumn burst can affect a growing season CH_4 fluxes for a few following years.

What this hypothesis fails to explain is why in the second half of the growing season (DASM 45–90) the fluxes were so similar between the years 2006–2009, but the first half of the next season remembered the state at the first half of the previous one. Further complicating our theory: let us suppose, that CH_4 emission during the growing season has two different components with different sources and mechanisms (Fig. 12).

The idea of fast and slow carbon turnover is not new (Chanton et al., 1995; Ström et al., 2005), so it may be assumed that the CH_4 peak in the first half of the growing season (Fig. 12a) has mainly slow carbon origin – say, from fine roots or soil

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microorganisms cells, damaged during previous freezing season (e.g. Soulides and Allison, 1961; Skogland et al., 1988). When the soil thaws, these organic compounds are involved in the bacterial turnover and part of them become methane. Such methane production goes on in the whole anaerobic horizon, including the locations, relatively far from the vascular plant roots, where the generated methane becomes entrapped and form bubbles. Such locations have limited capacities for storage of CH_4 and the more they fill, the more gas is migrating out, where it can meet plant roots and escape to atmosphere. After a few weeks this source of organic substrate depletes, and this type of methanogenic activity suspends until the next season. At the same time, another type of methanogenesis may be progressing – feeding on fast carbon, namely root exudates. This process is taking place in the rhizoshere, and only gathers its full rate when the vascular plants come to their maturity in the middle of the season. This methane is generated close to the roots, and finds its way through the plant tissues quite fast (background emission – Christensen, 1993). To large extend it escapes methanotrophic oxidation, so for this part of CH_4 the emission is directly controlled by production, production – by substrate availability, and substrate availability – by root exudation of certain vascular plants (Ström et al., 2012). This fast methane does not interfere with the subsurface storage pool, formed by early-season slow CH_4 production. As root exudation decreases with plants senescence, methanogenesis also decreases and so the emission (Fig. 12b). Then the soil starts to freeze, and under certain conditions slow methane has its chance to burst out (Fig. 12c). Thus the peak of growing season CH_4 emission (around DASM 30) and the freezing season burst are linked by the same source and storage pool, while the background CH_4 emission during second half of growing season is independent and related to plants.

The hypothesis of multisource character of CH_4 emission at our site may to some extent explain its different diurnal patterns throughout the season (Fig. 6). In the beginning of the season (Fig. 6a) the main source of CH_4 fluxes is slow methane, produced in the peat matrix. This flux should be relatively higher when diurnal temperature is high and entrapped bubbles are expanded, than when the temperature is low and the bubbles

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are condensed. During mid-season (Fig. 6b) the fluxes are mainly controlled by plants, and in conditions of midnight sun do not vary diurnally, contrary to low-latitude studies (Kim et al., 1999). During freezing season (Fig. 6c) the fluxes are mainly caused by water crystallization, so should be higher when the temperature goes down. The described mechanism corresponds with our data (Fig. 6), however, further studies are necessary to confirm or disprove its role.

The possible carry-over effects from one year to the next are emphasizing the importance of multi-year studies and the spatial heterogeneity of responses to the same drivers shows the need for integrated measurement approaches across space and time. Continued monitoring of methane emissions as presented in this paper are needed at multiple sites with multiple methods to improve our understanding of the controls on high-arctic emissions. The first five years of methane monitoring at Zackenberg have, hence, opened several basic questions to our conventional understanding of how methane emissions are controlled. Longer time-series at more sites will hopefully help provide answers to these questions.

Acknowledgements. The presented work has been carried out under the auspices of the GeoBasis part of the Greenland Ecosystem Monitoring program. The authors have seen support also from the Swedish Research Councils VR and FORMAS as well as the Linné Center LUCCI, the Nordic Center of Excellence DEFROST and recently the EU PAGE21 project.

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Table 1. Timing, temperature and flux values for five seasons, 2006–2010.

Key dates		2006	2007	2008	2009	2010
Snow melt	date	5 Jul	12 Jun	23 Jun	1 Jun	16 Jun
	DOY	186	163	175	152	167
= 0 °C at −5 cm	date	6 Sept	7 Sept	24 Sept	7 Sept	19 Sept
	DOY	249[a]	250	268	250	262
< 0 °C at −5 cm	date	23 Sept	24 Sept	10 Oct	4 Oct	4 Oct
	DOY	266[a]	267	284	277	277
< 0 °C at −15 cm	Date	–	7 Oct	19 Oct	24 Oct	18 Oct
	DOY	–	280	293	297	291
Growing season (days)		63	87	93	98	95
Zero curtain (days)		17	17	16	27	15
Freezing 5–15 cm (days)		–	13	9	20	14
Average air temperature (°C)						
Jun	absolute	1.03	3.31	4.98	1.76	2.25
	Δ10[b]	−1.02	+1.26	+2.93	−0.29	+0.20
Jul	absolute	6.62	5.88	8.82	8.22	5.61
	Δ10[b]	+0.81	+0.07	+3.01	+2.41	−0.20
Aug	absolute	5.51	6.60	6.93	4.95	6.48
	Δ10[b]	+0.67	+1.76	+2.09	+0.11	+1.64
Jun-Jul-Aug		4.43	5.28	6.93	5.01	4.80
Growing season		5.69	5.32	6.27	4.89	5.16
First 40 days of growing season		7.13	5.42	7.68	1.76	4.49
Growing season fluxes						
CH_4 average ($mg CH_4 m^{-2} h^{-1}$)		2.36	2.61	0.85	1.21	0.87
CH_4 total ($g C m^{-2}$)		2.68	4.09	1.42	2.13	1.49
CH_4 peak[c] ($mg CH_4 m^{-2} h^{-1}$)		4.6	6.5	1.8	2.2	2.6
CO_2 average ($mg CO_2 m^{-2} h^{-1}$)		−92.7	−130.9	−316.9	−58.9	−58.7
CO_2 total ($g C m^{-2}$)		−38.2	−74.5	−192.5	−37.8	−36.5
Post-season fluxes						
CH_4 average[d] ($mg CH_4 m^{-2} h^{-1}$)		–	4.26	0.11	0.92	0.55
CH_4 total,	$g C m^{-2}$	–	3.76	0.02	0.80	0.44
at least	% of GS	–	92 %	1 %	37 %	30 %
CO_2 average[d] ($mg CO_2 m^{-2} h^{-1}$)		–	405.3	–	151.3	336.9
CO_2 total,	$g C m^{-2}$	–	130.0	–	8.9	99.2
at least	% of GS	–	−174 %	–	−24 %	−272 %

[a] Temperature data from the main climate station.
[b] Average for the corresponding year minus average for previous 10 yr, 1996–2005.
[c] Maximal daily average within the growing season.
[d] For days when valid measurements exist

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Table 2. Ranking of 2006–2010 growing seasons in environmental conditions, CO_2 and CH_4 fluxes. Rank 1 means highest values, similar ranks mean close values.

Parameter	Interval, DASM	2006	2007	2008	2009	2010
Air temperature	0–30	2	3	1	5	4
	30–60	5	4	1	2	3
	60–90	5	2	3	1	4
Soil temperature	0–30	–	–	1	3	2
	30–60	–	3	1	2	4
	60–90	–	2	2	1	2
Water table level	0–30	1	2	3	3	4
	30–60	1	3	2	3	4
	60–90	–	3	1	2	4
Active layer thickness	0–30	3	1	2	1	2
	30–60	3	1	4	2	3
	60–90	–	1	3	4	2
Net CO_2 fixation	0–30	4	2	1	5	3
	30–60	–	2	1	2	2
	60–90	–	1	–	1	2
Net CH_4 emission	0–30	2	1	5	4	3
	30–60	1	2	3	3	4
	60–90	–	1	–	1	2

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Table 3. Linear and exponential correlation parameters between growing season average CH_4 flux (CH_4) and growing season averages for soil temperature at 5, 10 and 15 cm depths (T_5, T_{10} and T_{15}) and water table level (WTL).

Equation	Parameter	2007	2008	2009	2010
$CH_4 = a(T_5) + b$	R^2	0.85	0.08	0.76	0.91
	a	0.65	0.06	0.20	0.30
	b	−0.57	0.43	0.24	−0.16
$CH_4 = a(T_10) + b$	R^2	0.86	0.22	0.82	0.92
	a	0.74	0.10	0.22	0.36
	b	−0.36	0.21	0.24	−0.16
$CH_4 = a(T_{15}) + b$	R^2	0.73	0.60	0.72	0.57
	a	1.30	0.22	0.30	0.50
	b	−0.97	0.06	0.54	0.12
$CH_4 = a \cdot \exp(b \cdot T_5)$	R^2	0.86	0.19	0.63	0.91
	a	0.23	0.20	0.20	0.37
	b	0.67	0.10	0.38	0.17
$CH_4 = a \cdot \exp(b \cdot T_{10})$	R^2	0.88	0.41	0.71	0.90
	a	0.27	0.32	0.24	0.44
	b	0.71	0.06	0.37	0.17
$CH_4 = a \cdot \exp(b \cdot T_15)$	R^2	0.79	0.77	0.72	0.64
	a	0.48	0.55	0.34	0.64
	b	0.55	0.06	0.47	0.23
$CH_4 = a(\mathrm{WTL}) + b$	R^2	0.43	0.32	0.10	0.67
	a	0.20	−0.25	−0.11	0.06
	b	4.19	0.80	1.02	1.96
$CH_4 = a \cdot \exp(b \cdot \mathrm{WTL})$	R^2	0.45	0.18	0.10	0.57
	a	0.07	−0.38	−0.14	0.07
	b	3.64	0.46	0.73	2.02

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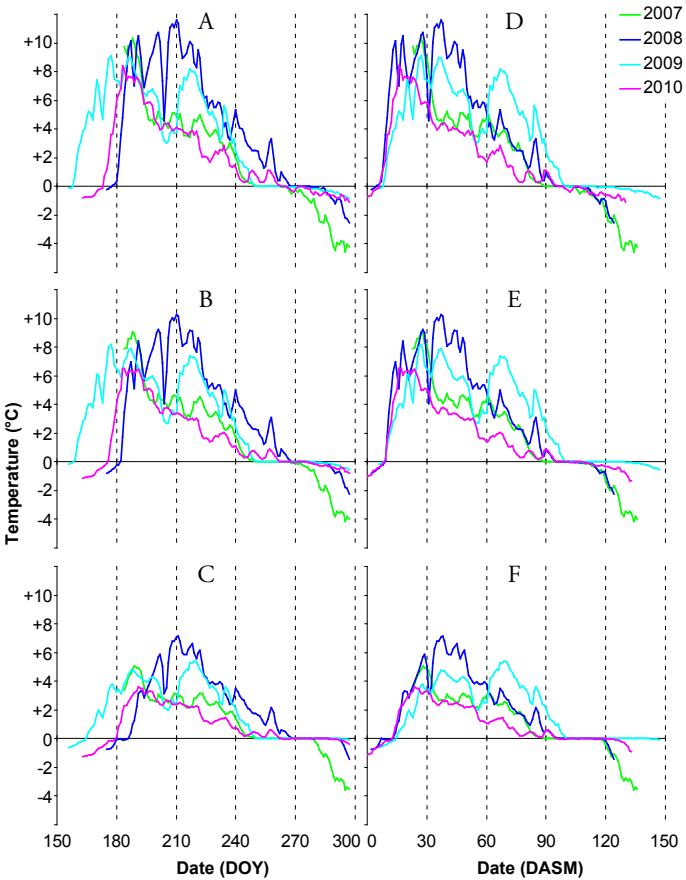

Fig. 1. Soil temperature dynamics at 3 depths. **(A, D)** 5 cm; **(B, E)** 10 cm, **(C, F)** 15 cm depth. **(A, B, C)** Normalized to day of year (DOY); **(D, E, F)** Normalized to day after snow melt (DASM).

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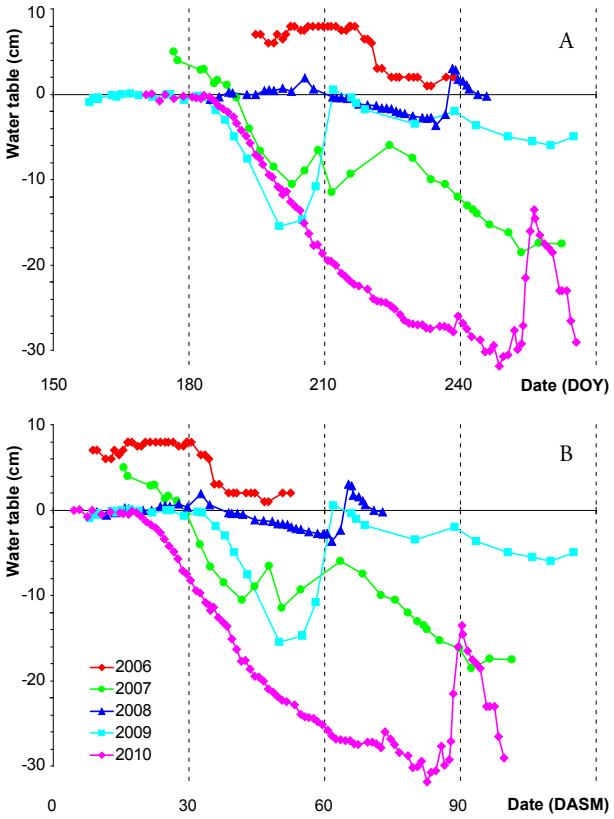

Fig. 2. Water table level dynamics. **(A)** Normalized to day of year (DOY); **(B)** Normalized to day after snow melt (DASM).

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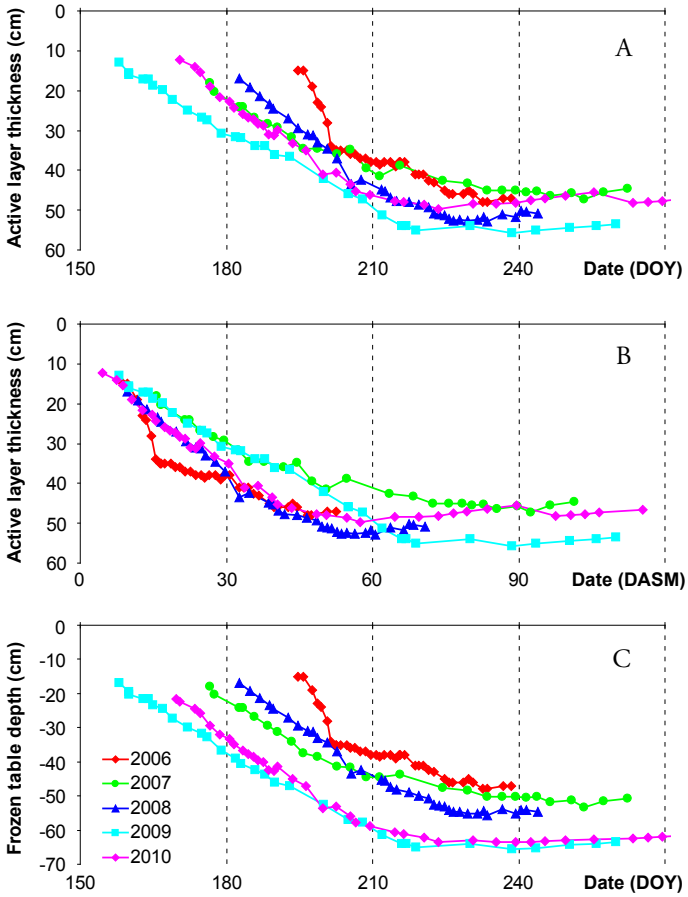

Fig. 3. Active layer dynamics. **(A, B)** Active layer thickness (depth relative to the surface); **(C)** Frozen table depth relative to the reference level. **(A, C)** Normalized to day of year (DOY); **(B)** Normalized to day after snow melt (DASM).

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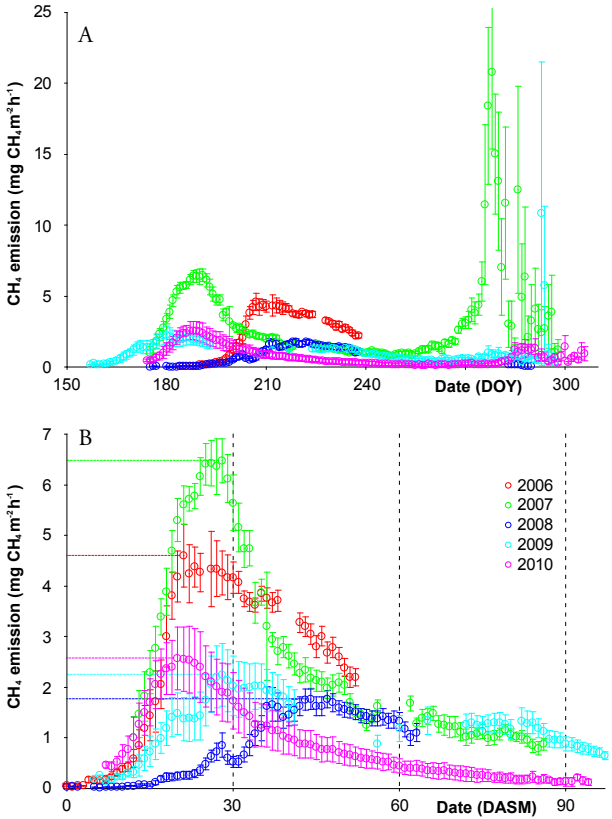

Fig. 4. CH_4 emission dynamics. **(A)** All measured fluxes, normalized to day of year (DOY); **(B)** Growing season fluxes, normalized to day after snow melt (DASM). Each circle states the average between daily averaged hourly measurements of 6 or less individual chambers; error bars state the standard error between daily average values of individual chambers.

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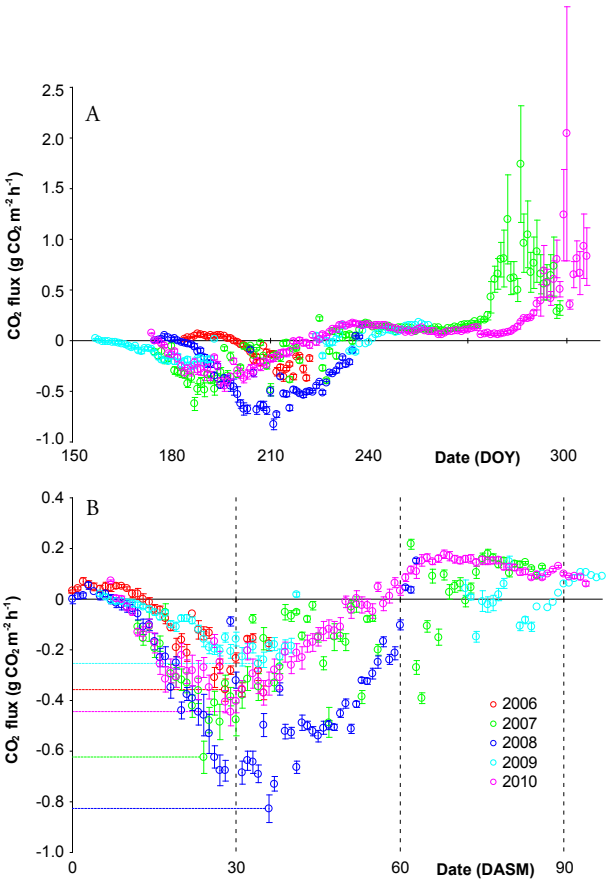

Fig. 5. CO_2 flux dynamics. **(A)** All measured fluxes, normalized to day of year (DOY); **(B)** Growing season fluxes, normalized to day after snow melt (DASM). Each circle states the average between daily averaged hourly measurements of 6 or less individual chambers; error bars state the standard error between daily average values of individual chambers.

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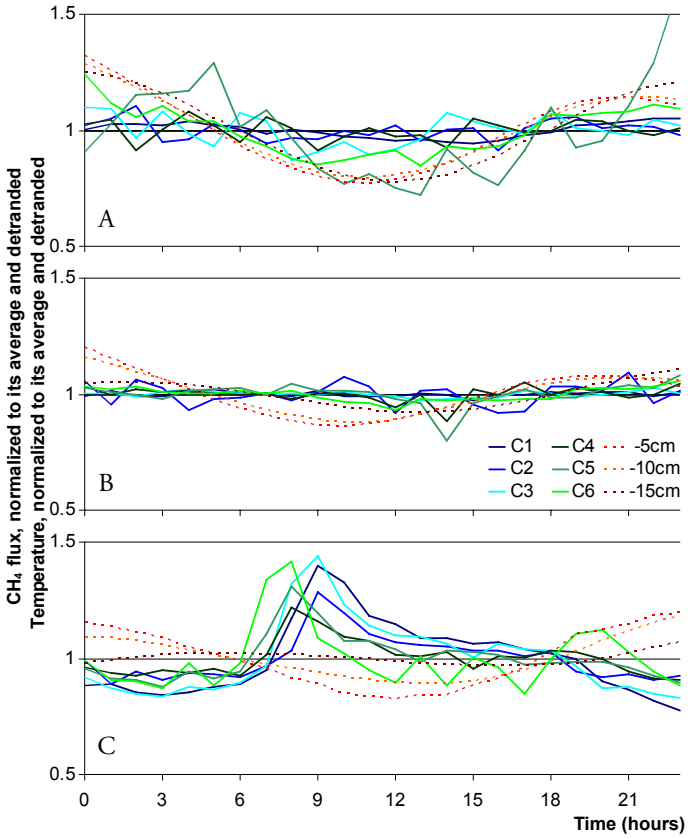

Fig. 6. Examples of diurnal dynamics of CH_4 fluxes and soil temperature. Full lines: CH_4 fluxes in individual chambers, normalized to their average and detrended; dotted lines: soil temperatures at 3 depths, normalized to their average and detrended. X scale: daytime, hours. **(A)** One week of data, DOY 165–171 (DASM 15–21), 2009. **(B)** One week of data, DOY 178–184 (DASM 28–34), 2009. **(C)** Two weeks of data, DOY 246–259 (DASM 96–109), 2009.

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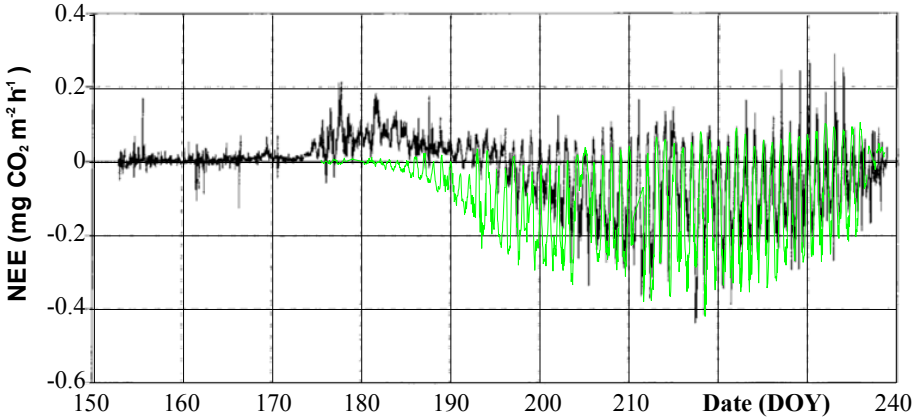

Fig. 7. A plot of NEE data 2008, green, over tower NEE data 1997 (Nordstrøm et al., 2001), black.

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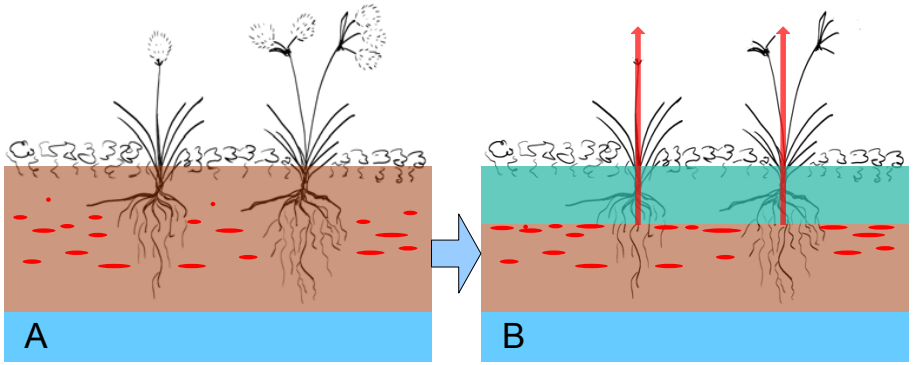

Fig. 8. Hyphotetical scheme of mechanism for late-season CH_4 and CO_2 emissions. **(A)** Summer; **(B)** Autumn. See the description in the text.

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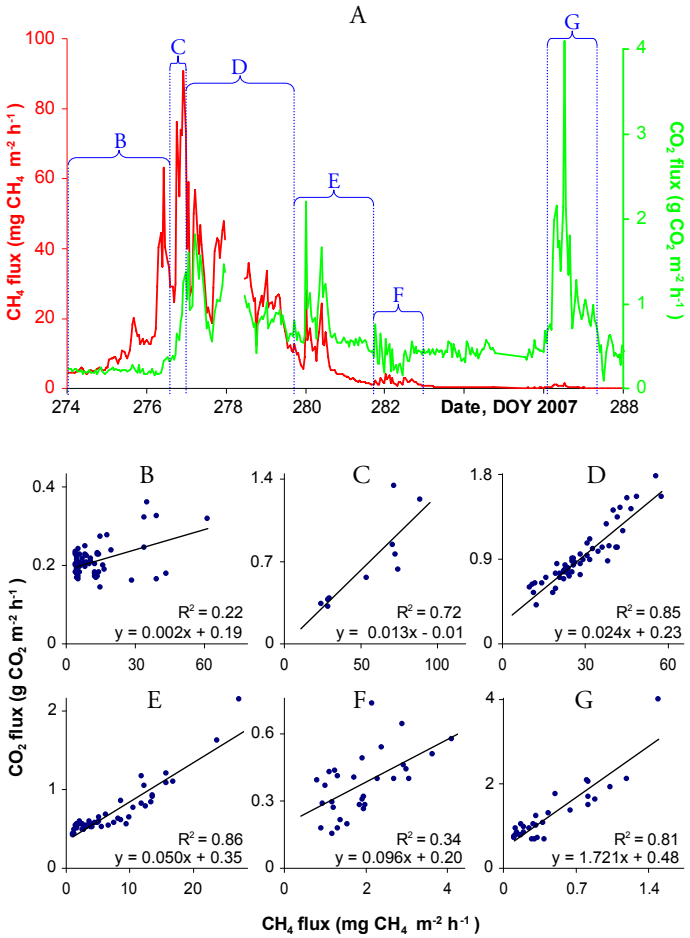

Fig. 9. Examples of freeze-in season dynamics of CH_4 and CO_2 fluxes in one of the chambers. **(A)** CH_4 (red, left axis) and CO_2 (green, right axis) fluxes. **(B–G)** CO_2/CH_4 ratio for individual intervals.

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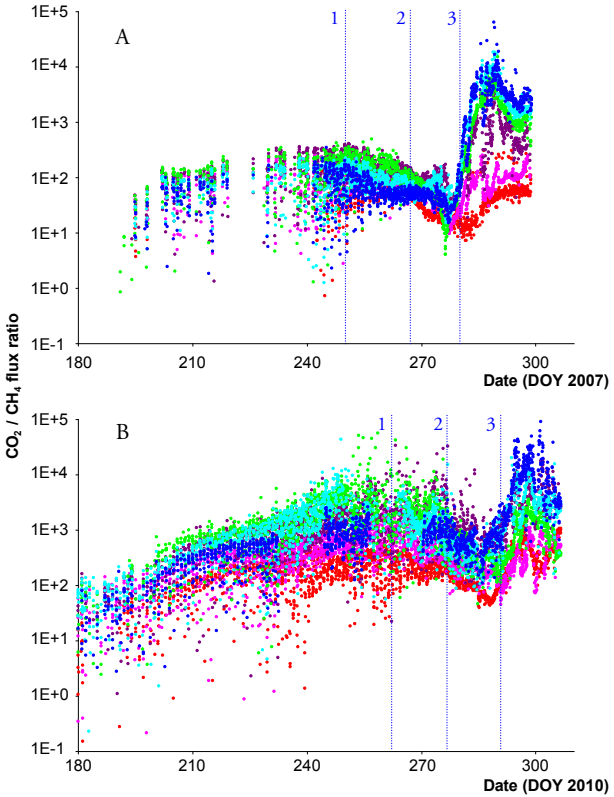

Fig. 10. Example of late-season correspondence between CH_4 and CO_2 fluxes. Six colors correspond to six individual chambers, each dot is CO_2/CH_4 ratio for one individual measurement. **(A)** 2007 data; **(B)** 2010 data. 1, 2, 3: time marks (see Table 1); 1: soil temperature at 0 °C, bound between the growing season and the freezing season; 2: soil is frozen to 5 cm depth; 3: soil is frozen to 15 cm depth.

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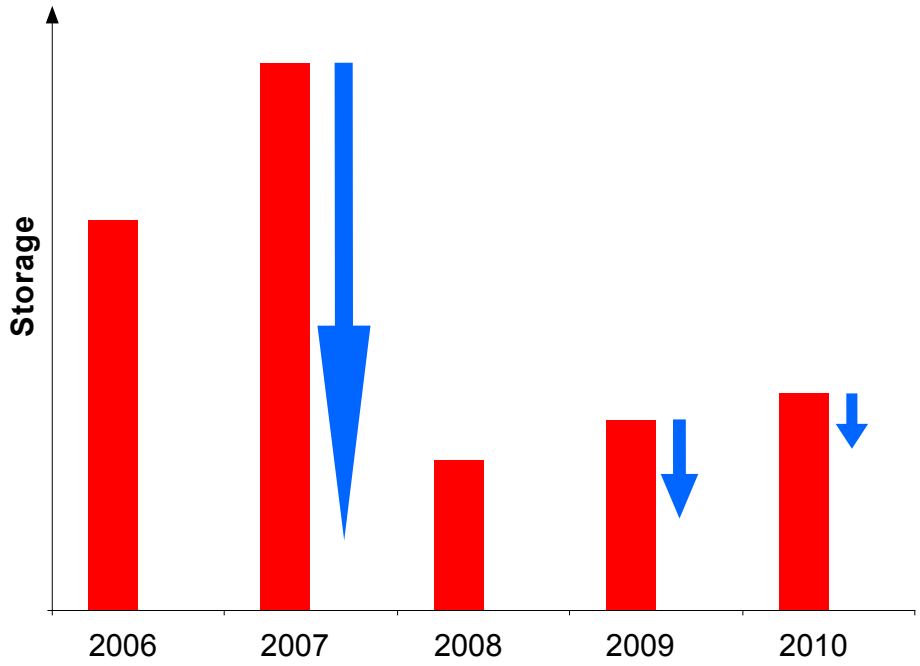

Fig. 11. Hypothetical scheme of subsurface CH_4 storage changes over five years. Red rectangles: storage pool during growing season; blue arrows: discharge during autumn burst.

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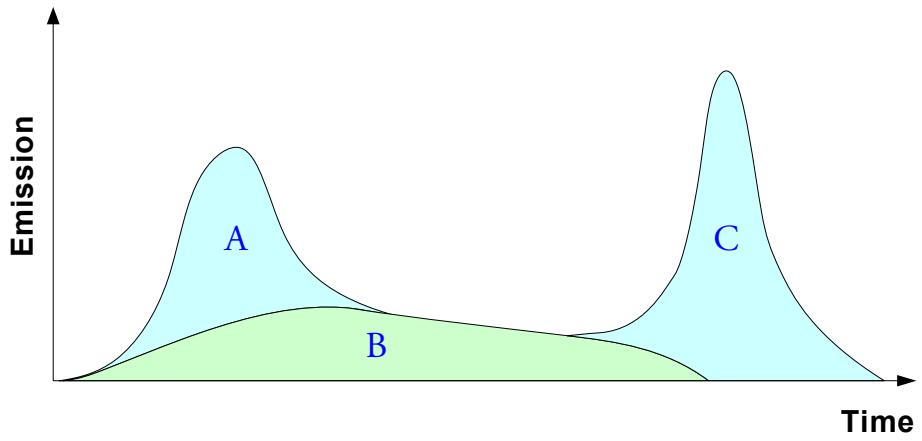

Fig. 12. Hypothetical scheme of bicompound CH_4 emission. **(A)** CH_4 based on slow carbon from freeze-thaw degraded matter; **(B)** CH_4 based on fast carbon from root exudation; **(C)** CH_4 stored in soil, mainly A-originated.

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