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Diurnal Variation in Methane Flux in a Low-Arctic Fen in Southwest Greenland

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Abstract

A study of diurnal variations in methane flux in a fen in Kobbefjord in Southwest Greenland is presented. Four separate periods, each of one week, from the growing seasons of 2009 and 2010 were chosen. Methane flux data were compared to surface temperature, soil temperature and photosynthetically active radiation (PAR). Regression tests between surface temperature and methane flux produced highly significant negative correlations ($p<0.01$) in the majority of cases in August 2009, and positive correlations at similar significance levels in August 2010. Correlations between PAR and methane flux showed a similar pattern at slightly lower significance. Correlations between soil temperature and methane flux were less evident. In addition to the analysis of the ambient flux data, an experiment was conducted in which the vegetation was darkened for five minutes at a time. In four out of five cases T-tests showed that flux levels were significantly higher in darkness ($p<0.05$). The observed negative correlations of methane flux to surface temperature and PAR may relate to reduced oxygen availability in the upper soil layers or in the rhizosphere. The available data are insufficient to explain why both positive and negative correlations were found at the same sites.

Der forelægges et studie af døgnvariationen i methanflux fra et kær i Kobbefjord i det sydvestlige Grønland. Studiet omhandler fire adskilte perioder, hver på en uge, fra vækstsæsonerne i 2009 og 2010. Methanfluxdata blev sammenholdt med overfladetemperatur, jordtemperatur og fotosyntetisk aktiv stråling (PAR). Regressiontests af overfladetemperatur og methanflux gav i august 2009 oftest stærkt signifikante negative korrelationer ($p<0{,}01$) og positive korrelationer med tilsvarende signifikans i august 2010. Korrelationerne mellem PAR og methanflux fulgte et lignende mønster med lidt lavere signifikans. Korrelationerne mellem jordtemperatur og methanflux var mindre tydelige. Udover analysen af de naturlige fluxdata indgik et eksperiment hvor vegetationen blev mørklagt i fem minutter ad gangen. T-tests viste at fluxniveauerne var signifikant højere i mørke ($p<0{,}05$) i fire ud af fem tilfælde. De negative korrelationer for metanflux mod overfladetemperatur og PAR kan skyldes begrænset ilttilførsel til de øvre jordlag eller til rhizosfæren. De tilgængelige data er utilstrækkelige til at forklare, hvorfor både positive og negative korrelationer kunne ses i de samme områder.

Contents

Introduction

Methane (CH_4) is produced by micro-organisms in the anaerobic zone of the soil (Koch *et al.*, 2007), which is mostly found below the water table. Freshly produced organic matter is the main substrate used by methanogenic bacteria in the production of methane. Plants release a range of organic compounds from their roots into the rhizosphere, including ectoenzymes, organic acids, sugars, phenolic compounds and amino acids, and this addition of fresh substrate has been observed to be an important source of carbon for the methane producing micro-organisms (Ström *et al.*, 2003). Methane produced in the soil can be transported to the surface along three different paths; diffusion, in bubbles rising through the soil profile (ebullition) or via the aerenchyma inside the roots, stems and leaves of vascular plants, which often contain large inter-cellular spaces (Hendriks *et al.*, 2010).

Diffusion of methane from below ground to the surface requires methane to pass through the aerobic zone of the soil near the surface. In the aerobic zone methane may be oxidised by methanotrophic micro-organisms, thus preventing it from reaching the atmosphere. Methanotrophic oxidation strongly influences methane flux from the soil to the atmosphere. According to various estimates 20–99% of methane can be oxidised in the aerobic zone (Ström *et al.*, 2005). This in turn means that factors controlling the consumption of methane in the aerobic zone may exert equally great influence on the final flux to the atmosphere as the factors controlling the production of methane in the anaerobic zone. However, methane transported to the atmosphere along the other two pathways is not to any significant degree subject to oxidation by methanotrophs.

Bubbles form in soil water where there are high concentrations of dissolved gases. Low air pressure and wind causing high near-ground air turbulence tend to increase methane flux by ebullition where there is open water or very wet conditions in the soil (Hendriks *et al.*, 2010).

Plant mediated transport of methane can be of major importance in determining the net flux of methane to the atmosphere from wetlands. In studies it has been observed to

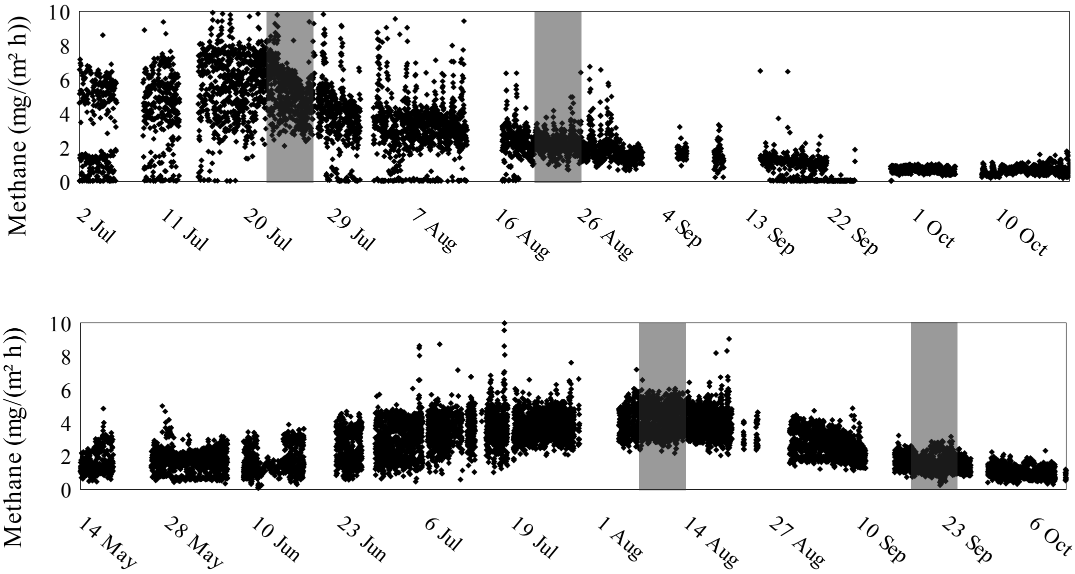

Figure 1. Methane flux measured during 2009 (top) and 2010 (bottom) with the four studied weeks shaded in.

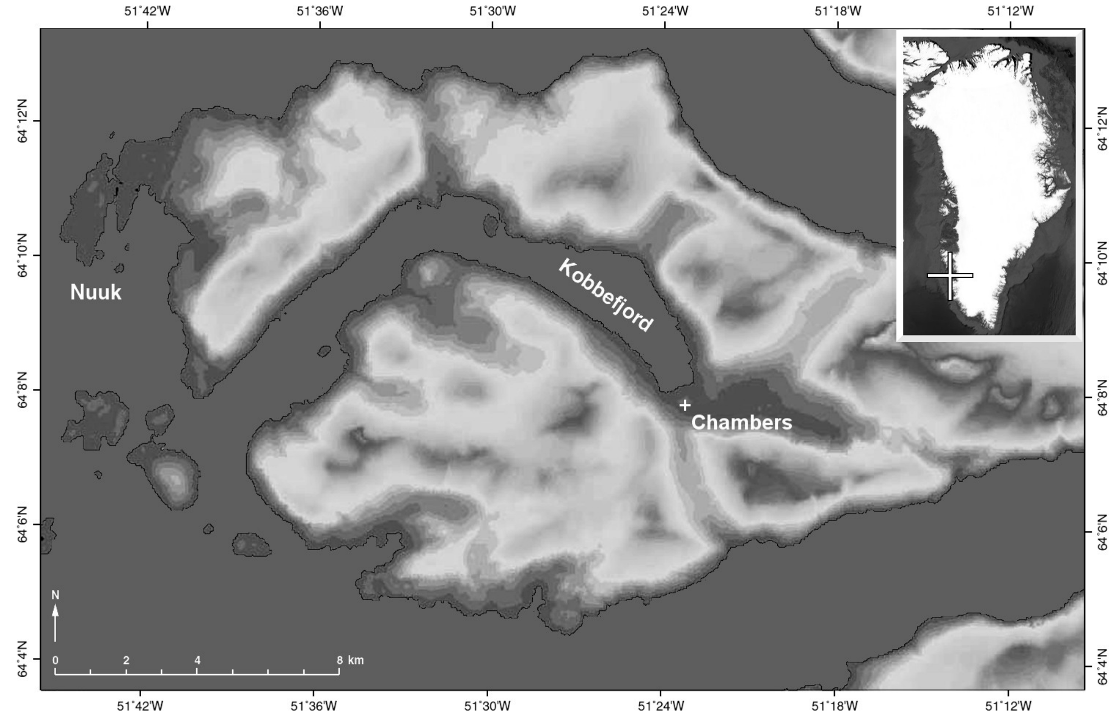

Figure 2. Map showing Kobbefjord and the location of the methane flux chambers. (Map of Kobbefjord: adapted from Bay *et al.*, 2008; map of Greenland: Marble, 2011)

account for 37–100% of the total methane flux (Koch *et al.*, 2007). Vascular plants have the ability to transport oxygen (O_2) to their roots, through the aerenchyma, but methane present in the rhizosphere may equally move in the opposite direction and be released into the atmosphere. The two directions of transport have the inverse effect of each other on methane flux, as the transport of methane through the stems of plants allows it to bypass the aerobic zone of the soil where it may be oxidised, hence resulting in increased flux to the atmosphere. Meanwhile, the release of oxygen into the rhizosphere creates an aerobic area inside the anaerobic zone where oxidation of methane can occur, causing a reduction of the flux to the atmosphere (Ström *et al.*, 2005). Whether the transport of oxygen to the rhizosphere or the transport of methane to the atmosphere has the greater effect on methane flux levels may vary depending on the specific case. The concentration of methane in the rhizosphere and the efficiency of methane oxidation around the roots of plants are factors that may influence this balance. The composition of plant species has also been observed to play an important role in determining methane flux to the atmosphere (Ström *et al.*, 2005).

In this paper I present a study of diurnal variation in methane flux in Kobbefjord in Southwest Greenland. The study aimed to establish if diurnal patterns occur in this site and to link possible patterns in variation to physical and biological parameters in the environment as a way of explaining how such patterns arise. Methane flux was measured in six automatic chambers placed in a wet fen (Jensen & Rasch, 2010). The chambers are operated as part of the Nuuk Basic research programme under Nuuk Ecological Research Operations (Jensen & Rasch, 2011). Data from 2009 and 2010 were used in this study. In 2009 flux measurements were made from early July until the middle of October and in 2010 from the middle of May until the middle of October. This means that the growing season and the time of highest methane flux are covered in the data series. In addition to the measurements of ambient flux an experiment was carried out in July 2010 to test what effect darkening had on methane flux levels. I have not been involved in planning and executing the experiment, neither have I had the opportunity to visit the research site. This study has therefore only involved processing the available data to identify patterns and their links to environmental parameters. Two hypotheses were tested; (1) diurnal variations in methane flux correlate with photosythetically active radiation (PAR) and (2) the variations correlate with temperature. In the former photosynthesis would be the main influence while in the latter both photosynthesis and respiration are influential. As null hypothesis, the flux patterns are independent of both variables.

Seasonal methane emissions in Kobbefjord (fig. 1) can be seen to increase towards a peak around late July to early August and then decrease into the autumn. Flux levels around the peak were higher in 2009 than in 2010.

Materials & Method

Site description

The research site is in a low-arctic environment in Kobbefjord (64° 07′ N, 51° 21′ W), approximately 20 km west-south-west of Nuuk, the Capital of Greenland (Jensen & Rasch, 2008).

Methane flux was measured in a wet fen with water table levels ranging from around 4 cm below to slightly above ground level during the study period. Figure 2 shows Kobbefjord and the site of the chambers. The vegetation of the fen was dominated by Mountain Bog-sedge (*Carex rariflora*), Deergrass (*Trichophorum caespitosum* syn. *Scirpus caespitosus*) and Common Cotton-grass (*Eriophorum angustifolium*) in the wettest areas, with Bog Bilberry (*Vaccinium uliginosum*) in a few drier places, as well as a high coverage of mosses (Bay *et al.*, 2008).

The weather in 2009 and 2010 differed in a number of ways. 2010 had little snow cover compared to 2009 and consequently the

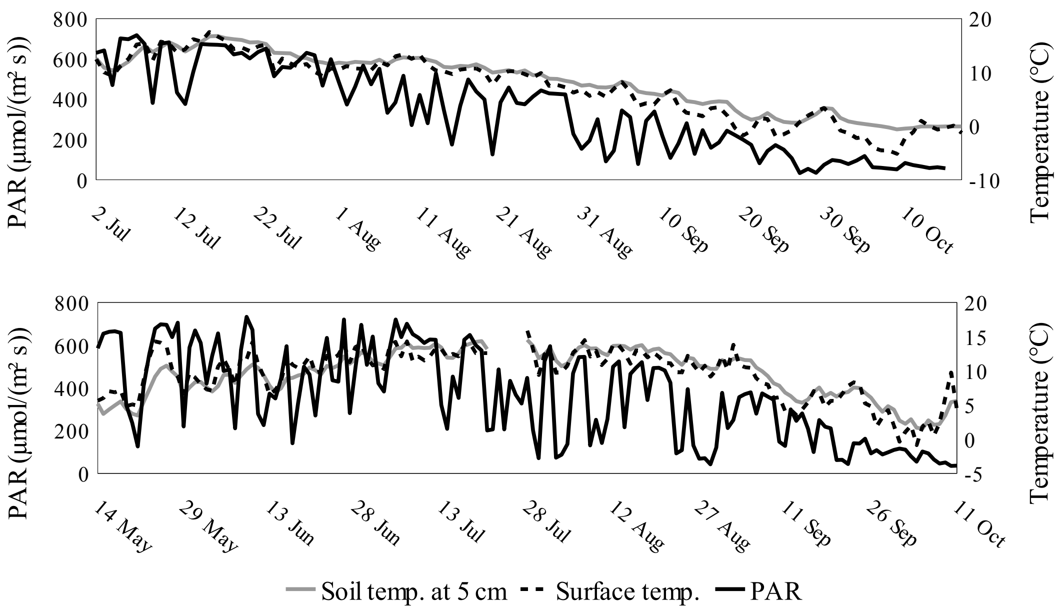

Figure 3. Diurnal mean of PAR, surface temperature and soil temperature at 5 cm depth in 2009 (top) and 2010 (bottom).

growing season started much earlier in 2010 than in 2009. The vegetation greenness threshold of 0.2 in the NDVI first occurred on 5 June 2009 and on 23 April 2010 (Jensen & Rasch, 2011). The warmest month of 2009 was July, while it was August in 2010. Temperature and PAR for the two years can be seen in figure 3.

The chambers

The chamber method is based on the notion that by isolating a known volume of air from the surroundings for a known period of time and measuring the change in concentration of the components concerned, in this case methane, actual quantities and flux can be deduced. The values obtained are valid for the area that the chamber covers at the time of measuring. Such information can be used to extrapolate more general patterns of methane flux in the area or to investigate spatial variation between the different chambers.

The chambers each consist of a case made of transparent plastic fitted on top of a base of aluminium which is fixed into the soil (Mastepanov, 2009). The chamber is sealed by a lid of transparent plastic which is opened and closed by a 12 V battery powered electric motor. The lid is vertically open when the chamber is inactive so that precipitation conditions will be similar inside and outside of the chamber, however strong winds can close the lid. When the chamber is activated the lid is opened or kept open for three minutes by the electric motor. During this time a fan inside the chamber flushes air through to ensure that the composition of air inside the chamber is identical to that of the outside. After three minutes of flushing the lid closes for five minutes during which changes in methane concentration are measured. Subsequently the lid reopens and the chamber is flushed through for an additional two minutes after which it is deactivated. Each chamber is thus active for 10 minutes every hour during which time the fan runs continuously to ensure an even distribution of gases inside. The measuring of methane is done by a central unit connected by tubing and power cables to all six chambers. Air from the chamber passes through a non-destructive methane analyser (DLT100, Los Gatos Research, USA), as well as a non-destructive carbon dioxide analyser, after which it is returned to the chamber. The chamber schedule is fixed to absolute time so that each chamber is always active at the same time every hour. Airflow to and from chamber one opens on the hour, analyses between three and eight minutes past the hour and then switches off at ten minutes past, at which time chamber two is activated and runs through the same cycle until twenty minutes past the hour and so on. The chambers are arranged in two lines running perpendicular to one another (fig. 4).

Figure 4. The chambers at the Kobbefjord site. One chamber is not visible in the picture. Photo courtesy of Lina Hällström.

Data collected

With one measurement of methane flux every ten minutes, 144 measurement were made per day; 24 for each chamber. PAR as well as a soil temperature profile at depths of 1 cm, 5 cm, 10 cm, 30 cm, 50 cm, 75 cm and at the soil surface were measured every 5 minutes. To get one value of these parameters for every flux measurement, the mean was calculated pairwise of two consecutive values. The level of the groundwater table was recorded every few days at each of the chambers during the whole season in 2010. Data for the groundwater table level is sparser in 2009, as measurements were less frequent and only made at one location which either was at chamber five or six (L. Hällström, personal communication, 2011).

Preprocessing of the raw methane flux datawas required in order to ensure data integrity. A gradual change in methane concentration is expected over the course of one measurement so if the observed pattern differs substantially from what would be expected, the measurement may be classified as bad. The data used for this study had already been pre-processed and bad measurements had been discarded. The processing results in scattered holes in the data series. Larger interruptions in the data series, visible in figure 1, occurred due to equipment failure as well as maintenance, calibration and repair (Jensen & Rasch, 2011). During 2009 chamber one was out of working order the whole season and chamber four through most of the autumn. During 2010 there were fewer malfunctions, but outages still occurred. The many interruptions in the methane flux data series caused limitations as to which periods during the two seasons that could be studied in sufficient detail. The data series for the other parameters, temperature and PAR, were almost intact for the entire two seasons.

The PAR measurements made at Kobbefjord were calibrated incorrectly, therfore data from the ASIAQ climate station a few kilometres away were used. Difference in weather between the two locations may cause inaccuracies, but diurnal and seasonal patterns of insolation should not differ substantially between the two locations.

Experimental darkening of the chambers

From 6–15 July 2010, an experiment was carried out to investigate what effect darkening of the chambers would have on methane flux. The chambers were covered with sheets of black plastic so that PAR levels measured inside the chamber were nought during the five minutes that the chambers were closed and active. When the chambers reopened, light was allowed in again. Darkening the chambers during the day meant that only PAR was decreased while other environmental factors, primarily temperature, remained comparatively unaltered. As PAR drops during night time, so does the air temperature and consequently any observed change in methane flux at night might be explainable by either of the two factors. Theoretically, the effect of PAR alone on methane flux should thus be observable in the experiment; however, covering the chambers in sheets of black plastic will likely have caused a cooling effect from the shade of the plastic and possibly a delayed warming effect due to its dark colour. Temperature was not measured inside the chambers so the extent to which it was affected by the experiment is not known, but presumably it was much less than the range of diurnal temperatures. Five of the chambers (2–6) were in working order at the time and were used in the experiment, which was run with 13 repetitions in each chamber.

Data assembly and treatment

In order to select data that would give a representative impression of diurnal patterns and allow insight into what mechanisms may control such patterns, a suitable period of study needed to be found. Studying individual 24-hour samples provides a great degree of detail, as every fluctuation through the day is visible, but comes with the risk that a given sample is poorly representative of overall patterns. Extreme values during a short sample period may lead to incorrect assumptions about longer term patterns. By calculating a mean 24-hour period from a longer sample period the data is temporally smoothed and distortions by extreme values are dampened. A disadvantage of such data smoothing is that important fluctuations may be evened out and will no longer visible in the mean values. There is no ideal solution, but a reasonable compromise can be found. After carrying out a set of test analyses on varying sample periods from 1–14 days, seven-day periods were chosen as a good compromise.

Selection of study weeks and objects

The study was focused on four separate periods of one week during 2009–2010; two each year. The choice of weeks was made so that they would display differences in methane flux, temperature and water table level. Two periods were in August either year in order to make comparisons of the two years possible. One week encompassed the autumn equinox so that there was equal time of day and night. One week lay early in the growing season in July 2009. Additionally, the weeks were selected to get as uninterrupted data series as possible, but despite this only five and four chambers respectively, were working during the two weeks in 2009. Week one was 21–27 July 2009, week two 19–25 August 2009, week three 7–13 August 2010 and week four 18–24 September 2010 (fig. 1). Both July and August 2009 had stable weather, frequently with clear skies and very little precipitation (Jensen & Rasch, 2010). The weather during the experiment in July 2010 was stable, but August was much wetter with 241 mm of precipitation. Equally, the weather turned unstable towards the last part of September (Jensen & Rasch, 2011).

Prior to calculating a mean 24-hour period from each of the weeks, the data was manually skimmed for abnormally high flux values, which in turn were deleted. Such values are likely to represent bubbles and are not relevant in the study of general diurnal patterns, as they are the product of the accumulated methane production of an unknown period of time.

The six chambers were treated separately in the data analysis because the difference in flux levels between the chambers often was greater than the diurnal range within one chamber. This shows that there is considerable spatial variation in methane flux within the Kobbefjord site, perhaps owing to spatial differences in water table level, soil type and vegetation. Mixing data between the chambers would give spatial smoothing and make it impossible to relate observations to ground water level data. Methane flux levels, surface temperature and PAR were analysed visually in charts as well as statistically.

Statistical analysis

The results from the experimental darkening of the chambers were run through T-tests for each chamber separately to assess whether there were significant differences between the fluxes in light and darkness. The fluxes were at similar magnitudes under light and dark conditions so Student's T-test was an appropriate choice as it assumes equal variance within the two populations (light and dark). Likewise, as the two populations are independent of each other, unpaired T-tests were applied. In the same way, the ambient flux measurements were divided into populations of light and dark for equivalent tests to be run for each week and chamber. The limit between light and dark was set at 10 $\mu mol/(m^2\ s)$ PAR and actual measurements from all seven days used, rather than the values from the mean 24-hour periods. This to retain a sharp division at 10 $\mu mol/(m^2\ s)$ PAR without any smoothing.

In addition to these tests, where PAR levels were treated in a binary manner with every value being classified as either '*light*' or '*dark*', the effect of gradual changes in PAR on methane flux was tested using simple linear regression for each chamber and week individually. These tests were performed on data from the mean 24-hour periods. Linear regression was also carried out for surface temperature and methane flux as well as for soil temperature at 5 cm depth and methane flux; in both cases with methane flux as the dependent factor. Statistical computations were conducted using R 2.13.0 (R Foundation for Statistical Computing, Austria).

Diurnal variation in soil temperature at depths below 10 cm amounted only to a few tenths of a degree within each of the studied weeks and is thus unlikely to be a major influence on the methane flux. As methane is produced under anaerobic conditions (Hendriks *et al.*, 2010), mainly below the water table, soil temperature at these depths may play an important role in controlling methane production on longer time scales, such as seasonal or inter-annual, but not within 24 hours.

Results

Methane flux under light and dark conditions

Experimental darkening of the chambers showed that significantly higher flux occurred in darkness than in light. Unpaired Student's T-tests run with the 13 measurements in darkness against an equivalent number of measurements in daylight, made on the same days, produced significant results in four out of five chambers at 95% confidence and at 99% confidence in three out of those four. Unpaired Student's T-tests of day and night populations from the four weeks, divided at the 10 µmol/(m² s) PAR mark, were run to test if the same significance could be observed in the ambient flux measurements. Since day and night were solely distinguished by PAR levels, they effectively represented light and dark as in the darkening experiment. For week 2 (August 2009) night time fluxes were higher than those at daytime in all active chambers with confidence levels far in excess of 99%. For the other three weeks, no significant difference at 95% confidence could be observed. In week 1 (July 2009) chamber six had higher flux at night with 90% confidence, but two other chambers had higher mean flux at day than at night. During week 3 (August 2010), mean daytime flux was higher in five out of six chambers and of those two showed significance at the 90% confidence level. During week 4 (September 2010) chambers two and six displayed higher mean flux in the day than at night, but none showed any significance, even at 90% confidence. By this time of the season methane flux levels had dropped to such a low level that fluctuations between individual measurements at times were as large as the total diurnal range. This makes diurnal patterns difficult to distinguish from noise. Visually, the methane flux in week 2 followed a gentle downwards sloping curve with its maximum around midnight and minimum around midday. This shape was not as evident during the other weeks. Examples can be seen in figure 5.

Response of methane flux to PAR, surface temperature and soil temperature

The response of methane flux to gradual changes in PAR was similar to that observed in the T-tests contrasting light and dark, in the sense that the highest degree of significance was observed in the same chambers and during the same weeks (Table 1). Similarly, positive and negative trends were distributed equivalently in chambers and weeks as above. Linear regressions with PAR as independent variable and methane flux as dependent showed significant trends in the F-tests ($p<0.05$) throughout week 2 and even higher significance ($p<0.01$) in three of the four active chambers. During week 1, two chambers produced significant results (both at $p<0.01$); in chamber three methane flux showed a positive correlation with PAR while in chamber six the correlation was negative. The correlation in chamber six was also visible in the T-test, albeit at lower significance. The correlation observed in chamber three was insignificant in the T-test. In week 3 chambers three and four, which showed 90% significance in the T-tests, as well as chamber five displayed positive correlations between PAR and methane flux at $p<0.01$. As above, there were no significant results in week 4. Overall, linear regression produced more significant results than T-tests.

Linear regressions with surface temperature as independent variable and methane flux as dependent produced similar results to those of PAR. This is not surprising, as PAR and surface temperature follow a similar pattern throughout the day. In most cases the F-tests gave higher significance with surface temperature than with PAR. This was true of all chambers during weeks 2 and 3, and all except chamber four during week 1. In week 4 correlations were weak.

With soil temperature at 5 cm depth as the independent variable and methane flux as dependent, the results were somewhat different from what they were with PAR and surface temperature. Generally soil temperature displayed lower significance levels than PAR and surface temperature, but with a number of exceptions, mainly in chambers two and six (table 1).

Matching methane flux to groundwater level

The level of the groundwater table has previously been observed to play a role in controlling methane flux in the Kobbefjord site (Jensen & Rasch, 2011). Water table levels measured during the four weeks range from -8 mm (above ground) to 38 mm (below ground). During the experiment water table levels ranged from 42 mm to 138 mm; at all

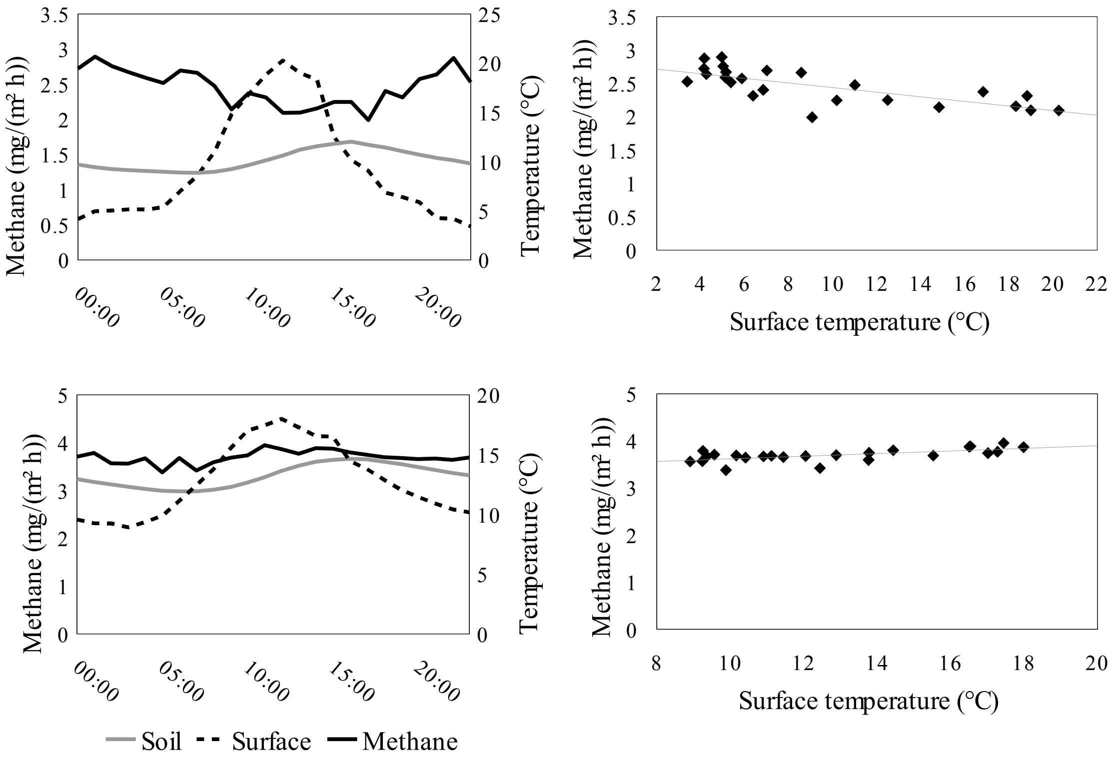

Figure 5. Mean diurnal methane flux, surface temperature and soil temperature at 5 cm depth in chamber five during week 2 (top) and week 3 (bottom). To the right are the corresponding linear regressions with surface temperature as independent factor and methane flux as dependent.

Table 1: Results of linear regressions of PAR, surface temperature and soil temperature against methane flux. Plus or minus indicates whether the correlation was positive or negative. The asterisks give the significance of the F-test; *=p<0.05, **=p<0.01, ***=p<0.001.

		PAR		Surface Temperature		Soil Temp. 5cm	
		R^2	F	R^2	F	R^2	F
Week 1 July 2009	Chamber 2	0.021 -	0.48	0.026 -	0.59	0.005 -	0.11
	Chamber 3	0.30 +	9.51**	0.31 +	9.73**	0.36 +	12.15**
	Chamber 4	0.01 +	0.23	0.004 +	0.085	0.051 +	1.17
	Chamber 5	0.009 -	0.20	0.024 -	0.55	0.11 -	2.61
	Chamber 6	0.29 -	8.85**	0.32 -	10.57**	0.32 -	10.16**
Week 2 Aug. 2009	Chamber 2	0.65 -	41.75***	0.66 -	42.79***	0.28 -	8.56**
	Chamber 3	0.19 -	5.01*	0.20 -	5.65*	0.027 -	0.61
	Chamber 5	0.54 -	26.31***	0.56 -	27.47***	0.39 -	14.16**
	Chamber 6	0.29 -	9.17**	0.32 -	10.48**	0.41 -	15.36***
Week 3 Aug. 2010	Chamber 1	0.002 +	0.051	0.005 +	0.11	0.052 +	1.22
	Chamber 2	0.11 +	2.64	0.19 +	5.01*	0.30 +	9.35**
	Chamber 3	0.33 +	11.06**	0.44 +	17.25***	0.36 +	12.52**
	Chamber 4	0.48 +	20.45***	0.53 +	25.29***	0.34 +	11.15**
	Chamber 5	0.30 +	9.34**	0.40 +	14.46***	0.35 +	11.88**
	Chamber 6	0.013 +	0.28	0.03 +	0.68	0.053 +	1.23
Week 4 Sep. 2010	Chamber 1	0.073 -	1.72	0.026 -	0.58	0.011 +	0.24
	Chamber 2	<0.001 +	0.005	<0.001 -	0.004	0.029 +	0.67
	Chamber 3	0.062 -	1.45	0.054 -	1.25	0.001 +	0.031
	Chamber 4	0.01 -	0.22	0.046 +	1.07	0.17 +	4.62*
	Chamber 5	0.007 +	0.16	0.01 +	0.22	0.007 +	0.16
	Chamber 6	0.043 +	1.00	0.016 +	0.35	0.011 -	0.26

times lower than during the four weeks. Although the weather during the study weeks of 2009 was drier than during those of 2010, it is likely that the water table level was higher in weeks 1 and 2 than in weeks 3 and 4. Ground water data is only available for one chamber in 2009; it is uncertain whether this was chamber five or six (Hällström, L., personal communication, 2011). Comparing the data from 2009 to the water table levels of chambers five and six in 2010, it appears that the two weeks in 2009 had higher groundwater levels than those in 2010. However, in 2010 the relative level of the water table between the chambers differed through the season, therefore the extrapolation comes with great uncertainty. The soil in chamber four was waterlogged in week 4 and probably this was also the case in weeks 1 and 2. Even in chamber three the soil may have been waterlogged in weeks 1 and 2.

Correlations of the three factors (PAR, surface temperature and soil temperature at 5 cm depth) to methane flux are mostly negative in weeks 1 and 2, meaning that methane flux was higher at night than at day. In week 3 the correlations are positive in all chambers. This could be a tendency towards increased night time flux at high water table level and increased daytime flux at lower water table level. The tendency is weak, though; the difference in water table level between week 2 and week 3 (chamber five) was less than 1 cm and the most significant positive correlations in week 3 are found in the chambers that generally have the highest water table levels (three and four).

Discussion

Ambient flux measurements

Surface temperature and PAR follow a similar pattern through the day and night; PAR slightly ahead of temperature (fig 6). In a given chamber and week, methane flux therefore correlated either with both or neither of those two factors. PAR affects photosynthesis, which in turn controls the availability of oxygen and substrate in the rhizosphere (Ström *et al.*, 2005). Surface temperature also influences photosynthetic rate as well as the rate of methane oxidation in the uppermost layers of the soil. Both factors thus have positive and negative effects on methane emission. During week 2 (August 2009), PAR and surface temperature showed significant negative correlations with methane flux in all chambers. Regarding the two above mentioned mechanisms, such a pattern may be explained by a decrease in oxygen supply to the rhizosphere, or by a reduced rate of oxidation in the upper soil layers, due to lower temperature. The same pattern is visible in the experimental darkening of the chambers, indicating that the same mechanism may be responsible in both cases. If so, the mechanism must be effective in just five minutes. This will be discussed in more detail later. In week 3 (August 2010), PAR and surface temperature produced positive correlations with methane flux in three and four chambers respectively; the highest degree of significance was with surface temperature. This implies a positive response to photosynthesis.

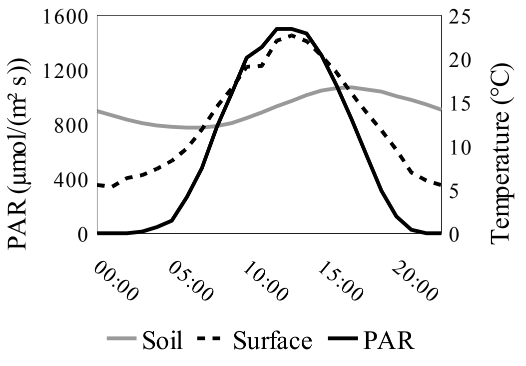

Figure 6. 24-hour mean of PAR, surface temperature and soil temperature at 5 cm depth in week 1, chamber four. PAR and surface temperature follow a similar pattern throughout the day, while soil temperature exhibits dampening and delay in relation to the other two.

Due to insulation, the soil temperature at 5 cm depth shows dampening and time delay in relation to surface temperature. During the four study weeks, the water table was at no point below 5 cm so in all cases the temperature at this depth would have influenced processes occurring under the water table. This could suggest that methane production rather than oxidation was the main process, but it is uncertain as it depends on the oxygen availability in the root zone. The correlation between methane flux and soil temperature was overall weaker than with the other two factors, but without any details of oxygen availability at this depth it is difficult to deduce anything from the results.

Some studies have not found any diurnal variation in methane flux (Rinne *et al.*, 2007; Sachs *et al.*, 2008; Jackowicz-Korczyński *et al.*, 2010), while others have. The observed variation frequently shows higher fluxes in the day and lower at night (Brix *et al.*, 1996; Thomas *et al.*, 1996; Whiting & Chanton, 1996; Ding *et al.*, 2004; Hirota *et al.*, 2004; Wang & Han, 2005; Chen *et al.*, 2010; Hendriks *et al.*, 2010), but some studies have also observed increased fluxes at night. Mikkelä *et al.* (1995) and Koch *et al.* (2007) both observed that methane emissions were highest at night in places where the water table level was low and highest at day where it was high. Mikkelä *et al.* (1995) attributed this to an inhibition of methane oxidation above the water table due to low night time temperatures, or to a delay in the supply of substrate, or both. The sparse data of groundwater table levels in 2009 in Kobbefjord mean that this explanation can only be applied to the observed patterns with much uncertainty. It seems probable that the water table was higher in week 2 than in week 3 which would indicate that night time fluxes in Kobbefjord are higher when the water table is high. However, as the relative depth of the water table between the chambers varies in 2010, nothing certain can be deduced about 2009. One study found that at a single site the methane flux displayed all of the following patterns: no diurnal variation, higher flux at night and higher flux at day at different times within a period of two months (Nakano *et al.*, 2000). Here methane flux correlated with soil temperature at varying depths. Higher daytime flux has been attributed to surface temperature (Whiting & Chanton, 1996) and photosynthetic activity (Wang & Han, 2005). The reason why correlations of methane flux to PAR and temperature in Kobbefjord are sometimes positive and sometimes negative is not clear from the available data. It could well be that several controlling factors are active in determining net methane emissions.

Experimental darkening

The experimental darkening of the chambers in July 2010 resulted in significantly higher flux during darkness in four out of five chambers. Similar darkening experiments have been conducted in other studies over varying periods of time (Holzapfel-Pschorn *et al.*, 1986; Joabsson & Christensen, 2001; Ding *et al.*, 2004; Hirota *et al.*, 2004; Wang & Han, 2005). A rapid response to darkening was seen in one experiment where stomatal closure caused a decrease in methane flux of up to 80% after 30 minutes of darkening (Hirota et al., 2004). Contrary to this, Wang & Han (2005) observed no change in flux within 30 minutes, but after three days a decrease explained by stomatal closure and reduced substrate availability was seen. Holzapfel-Pschorn *et al.* (1986) found no change in methane emissions from rice plants (*Oryza sp.*) after three days of darkening, while Ding *et al.* (2004) measured a significant increase in flux over three days in a *Carex lasiocarpa* dominated plot. They speculated that the net effect of gas transport in *Carex lasiocarpa* may be to increase oxidation in the root zone rather than to increase methane flux out of it. In the last experiment PAR was reduced by around 60% for the whole season resulting in reduced methane emissions, caused by decreased substrate quality and root transport (Joabsson & Christensen, 2001).

Since PAR was the only factor that was manipulated in the experiment in Kobbefjord, it is likely that the responsible mechanism or mechanisms are dependent on photosynthesis. Decreased flow of oxygen, either to the rhizosphere or to the upper layers of the soil are possible causes. The methanotrophs in the aerobic zone of the soil might be acutely dependent on oxygen released from low growing plants, such as mosses. Inhibiting photosynthesis by darkening could cause oxygen starvation, leading to reduced methane oxidation. This is, however, purely a speculation. If, on the other hand, a reduced flow of oxygen through the aerenchyma is responsible, then it would mean that the effects of oxygen transport outweigh those of plant mediated methane transport and substrate supply. This would correspond well with the results of Ding *et al.* (2004), provided that *Carex lasiocarpa* has similar characteristics to *Carex rariflora*, found in the Kobbefjord site (Bay *et al.*, 2008). The response seen in Kobbefjord was, however, much faster. Furthermore, it is worth mentioning that Hirota *et al.* (2004) measured no change in methane flux in a *Carex allivescers* dominated plot under experimental darkening. To ascertain if decreased oxygen flow may provide valid explanations in either of the two scenarios outlined above, the darkening experiments could be repeated with added monitoring of the redox potential, as an indicator of oxygen availability, in the upper soil and root zone.

As an alternative explanation of the increase, people walking near the chambers while they were being covered with black plastic sheets, just before the measurements were carried out could have forced bubbles out of the soil and into the chambers.

Conclusions

During the four study weeks, diurnal methane flux patterns showed a high degree of correlation with surface temperature and a slightly lesser with PAR. Highly significant positive and negative correlations were both observed. From the available data it is not possible to determine whether changes in methane flux came about in response to mechanisms controlled by PAR, or temperature, or both. There may have been a connection to the groundwater table level, but this is difficult to ascertain.

Experimental darkening produced significant results between PAR and methane flux. It is not clear from the results which mechanism caused this, but it may relate oxygen supply and possibly to plant species composition.

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