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TELLUS

Diurnal dynamics of CH_4 from a boreal peatland during snowmelt

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ABSTRACT

Peatlands are one of the major natural sources of methane (CH_4), but the quantification of efflux is uncertain especially during winter, fall and the highly dynamic spring thaw period. Here, we report pronounced diurnal variations in CH_4 fluxes (F_{CH4}), measured using the eddy-covariance technique during the snow-thawing period at a boreal peatland in north-western Russia. Following the background winter emission of $\sim$0.5 mg m^{-2} h^{-1}, strong diurnal variability in CH_4 fluxes from 21 April to 3 May was apparently controlled by changes in surface temperature (T_{sur}) and near-surface turbulence as indicated by the friction velocity (u^*). CH_4 fluxes were $\sim$0.8 mg m^{-2} h^{-1} during night and $\sim$3 mg m^{-2} h^{-1} during peak efflux. Primarily, the freeze-thaw cycle of an ice layer observed at the wet peatland microforms due to surface temperatures oscillating between >0°C during the days and <0°C during the nights appeared to strongly influence diurnal variability. Once the ice layer was melted, increases in wind speed seemed to enhance CH_4 efflux, possibly by increased mixing of the water surface. Apparently, a combination of physical factors is influencing the gas transport processes of CH_4 efflux during the highly dynamic spring thaw period.

1. Introduction

Wetlands are a major natural source of methane (CH_4) to the atmosphere (Denman et al., 2007). The majority of natural wetlands are situated in the boreal region (Fischlin et al., 2007). Generally, most of the CH_4 is released during the short growing season; however, recent literature from cold tundra region reported greater autumnal emissions than was observed during the growing season (Mastepanov, 2008). CH_4 efflux is mainly controlled by soil temperature, water table (WT) position (Bubier et al., 1993; Thomas et al., 1996; Bellisario et al., 1999; Christensen et al., 2003) and organic acid concentrations (Christensen et al., 2003). In water-logged environments, near-surface turbulence appears to play an important role for CH_4 emissions (Hargreaves et al., 2001; Sachs et al., 2008; Wille et al., 2008). Temporal fluctuations in CH_4 flux (F_{CH4}) during the growing season are driven by several factors, for example, temperature effects on decomposition of soil organic matter and subsequent CH_4 production, plant photosynthesis and carbon translocation to roots and plant-mediated transport of CH_4 (Mikkelä et al., 1995; Thomas et al., 1996). Short-term correlation of surface temperature and diurnal variation in CH_4 flux found in some microsites during the growing season indicates that control mechanisms of CH_4 emission are changing over the growing season (Kettunen, 2002). Due to diverse peatland microtopography, CH_4 efflux can show high-spatial variability (Bubier et al., 1993; Becker et al., 2008).

Despite the dominant role of the vegetation season for the CH_4 balance, non-zero CH_4 fluxes during the cold seasons can contribute significantly to the annual CH_4 emissions, with estimates ranging from 3.5 to 21% (Dise, 1992; Panikov and Dedysh, 2000). From the long cold season, the short thawing period at the end of winter and the period right after the snowmelt are of high interest. During the snowmelt period, CH_4 fluxes can dynamically change over short times, amounting to 11% of the annual CH_4 budget (Hargreaves et al., 2001), while spring emissions after snowmelt can amount to 24% or even 77% (Comas et al., 2008). Thus, in some cases, the spring emissions after the snowmelt can even exceed the emission during the vegetation period. High temporal variability in CH_4 fluxes during the spring might also include diurnal variations possibly caused by freezing and refreezing of the surface water as hypothesized by Tokida et al., (2007). During the snow-thawing period 2008, we have observed pronounced diurnal variations in CH_4 fluxes from

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a boreal peatland in Komi Republic, Russia, lasting for several days. In this paper, our objective was to further elaborate the above-mentioned hypothesis, and to try to explain the process of diurnal variations in CH_4 fluxes during this particular period.

2. Site and methods

The study site is located in the 25 km^2 mire complex 'Ust Pojeg' (61°56'N, 56°13'E) near the village of Sludka, approximately 60 km north-west of Syktyvkar, the capital of Komi Republic, Russia (Fig. 1). The climate is boreal continental and humid with maximum precipitation in summer. The measurement system was set up in the south-western part of the peatland accessible via a 1300-m-long boardwalk, passing different ecosystem types from swampy birch-pine forest to open peatland. The eddy-covariance tower was placed at the border between a minerogenic part of the peatland in the south-west and an ombrogenic part in the north-east with the transition zone in-between. The minerogenic depression, close to the eddy-covariance system was somewhat lower in elevation resulting in higher WT during parts of the study period, compared to the other parts of the peatland (Fig. 2). The dominant moss vegetation cover is *Sphagnum angustifolium* in the ombrogenic bog part and *S. jensenii* and *S. fuscum* in the minerogenic fen part. *Carex limosa* and *Scheuchzeria palustris* dominate in hollows; *Andromeda polifolia, Chamaedaphne calyculata, Betula nana* and *Pinus sylvestris* dominate on hummocks. Vegetation on lawns is a mixture of hummock and hollow vegetation with *Vaccinium oxycoccus.* The occurrence of *Menyanthes trifoliata* and *Utricularia intermedia* indicates greater nutrient supply in the minerogenic part of the mire. *Carex rostrata* dominates in the transition zone between bog and fen. The average depth of the peat is ∼2 m.

Fluctuations of wind speed components were measured 3 m above the surface using a three-dimensional sonic anemometer (Solent R3, Gill Instruments Ltd., Lymington, UK). The air from the sample intake was drawn by a vacuum pump through a 12-m long, 8-mm inner diameter tube and a fast CH_4 analyser RMT-200 (Los Gatos Research Inc., Mountain View, California, USA) where the fluctuations of CH_4 concentrations were measured. Before entering the RMT-200, the sample air was dried using a gas dryer (Perma Pure Inc., New Jersey, USA). Data were logged at 20 Hz, and the eddy-covariance fluxes were calculated over 30-min intervals. The time lag between wind and CH_4 concentration measurements was determined and removed for every averaging period. Turbulent fluxes were calculated using the EdiRe software (Robert Clement, University of Edinburgh, Edinburgh, UK; version 1.4.3. 1184). Flux losses due to the limited frequency response of the eddy-covariance system were corrected in the flux-calculation process. The fluxes were corrected for the frequency attenuation due to tube attenuation, sensor path separation and spectral response of the instruments (Moore, 1986; Moncrieff et al., 1997). On average, 11% were added to the calculated CH_4 flux. Data obtained during conditions that violated basic assumptions of the eddy-covariance theory were rejected using filters evaluating integral turbulence characteristics and stationarity (Foken and Wichura, 1996). By these procedures, 13% of the data were removed. No data gap filling was applied.

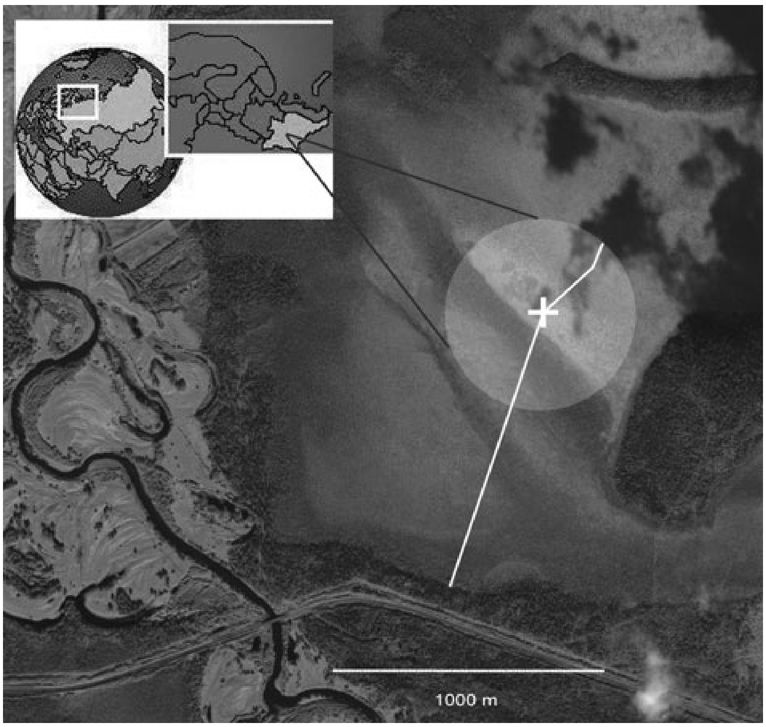

Fig. 1. Aerial picture of the study site (Quickbird; 8 July 2008) in the Komi Republic, Russia. The white cross represents the position of the eddy-tower accessible via boardwalk (white line). The circle shows an approximate fetch of 300 m in radius. The wide dark stripe in the fetch is the border between the minerogenic and ombrogenic part (minerogenic depression). Dark areas in the upper ombrogenic part are clouds.

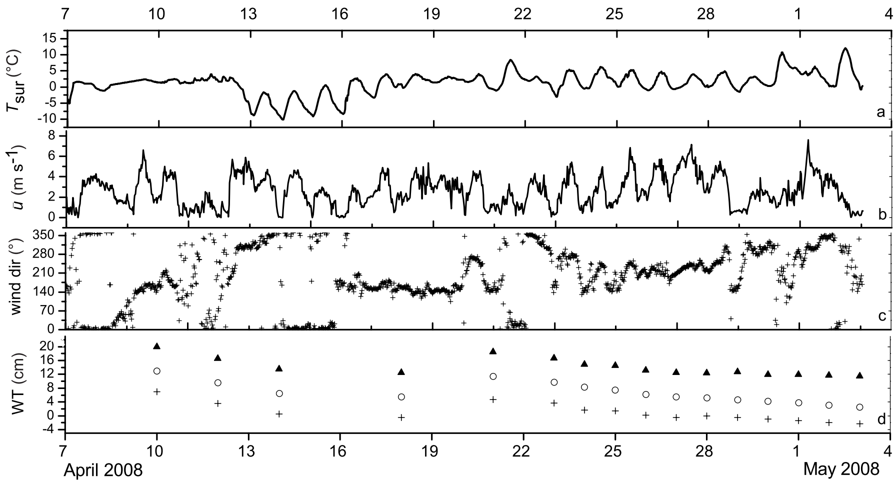

Fig. 2. Meteorological and environmental conditions on Ust Pojeg peatland in the early spring period 2008: (a) surface temperature, (b) mean wind speed, (c) wind direction, (d) water table; (▲) minerogenic depression, (○) ombrogenic part and (+) transition zone. In a, b and c 30-min averages, in d daily averages are displayed.

Supporting meteorological measurements of air temperature, wind components, barometric pressure, relative humidity and net radiation were logged at a climate station installed at the eddy-covariance site. The surface radiative temperature T_{sur} (°C) was calculated from outgoing long-wave radiation, using the Stefan-Boltzman law and an emissivity of 0.98.

Linear and exponential functions were fitted to the data with different environmental factors as explanatory parameters. The best model performance was obtained when CH_4 flux was modelled as a linear function of surface temperature ($r^2_{adj} = 0.50$ linear vs $r^2_{adj} = 0.41$ for the exponential function). Reduced major axis (RMA) regression was then applied because we assume that the signal-to-noise ratio of the explanatory variable surface temperature is similar to that of CH_4 flux.

3. Results

3.1. Temperature characteristics and snowmelt dynamic

When CH_4 flux measurements started on 6 April 2008, the surface was completely covered with a snow layer of ~40 cm depth, only some hummocks protruded out of the snow and snowmelt had just started. The meteorological conditions during the study period are shown in Fig. 2. There was minor rain on 9 April (observed but not measured), on 10 April (1.2 mm), 11 April (7.4 mm) and 12 April (4.8 mm). After 12 April, colder weather slowed down snowmelt and caused partial re-freezing of the snowmelt water and peat surface. From 16 April, all snow was melted causing a rise in the WT. Water was standing above the surface in many parts in ombrogenic and minerogenic areas. Hummocks were free of water, but the WT position was usually close to the surface. The precipitation from 18 to 20 April of 9.4 mm contributed to an increase of WT height. From 21 April to 3 May, pronounced fluctuation of daily temperatures caused freezing of water and peat surface during the nights, with the exception of a few nights. During this period, the WT in the minerogenic depression dropped from +17 cm to +11 cm above the peat surface. In the ombrogenic zone, the WT dropped from +12 cm above the peat surface to +3 cm; in the transition zone, from +5 cm above to 2 cm below the surface (Fig. 2).

3.2. CH_4 flux

CH_4 was emitted steadily from the site at the beginning of the measurements. Average hourly CH_4 flux above the snow surface was $\sim 0.54 \pm 0.17\,\mathrm{mg\,m^{-2}\,h^{-1}}$. April 9 and 10 were windy, and hourly fluxes increased to an average of $\sim 0.78 \pm 0.28\,\mathrm{mg\,m^{-2}\,h^{-1}}$ and $\sim 0.88 \pm 0.23\,\mathrm{mg\,m^{-2}\,h^{-1}}$, respectively. Technical problems from 11 to 21 April restrained measurements. From 21 April on, pronounced diurnal variations in CH_4 fluxes were recorded (Fig. 3). The fluxes reached peak values of $>3\,\mathrm{mg\,m^{-2}\,h^{-1}}$ in the early afternoon (~1400 to 1600 local time (LT); UTC+4), followed by a steady decrease and a minimum in the early morning (~0400 to 0900 LT) (Fig. 3). During the period described, the most frequent wind directions were SE and N with winds coming from the minerogenic part (roughly from 120° to 300°; 0° = N) being more common. In general, lowest wind speeds occurred during night and usually highest at late afternoon.

From 21 April to 3 May, the period of strong diurnal changes, CH_4 flux was strongly correlated with T_{sur}; $r = 0.71$. An empirical linear model based on RMA regression with surface temperature as a predictor was used to model the flux time series (Fig. 3) as follows:

$$F_{CH4} = 1.413 + 0.211\ T_{sur},\ r^2_{adj} = 0.50;\ \mathrm{RMSE} = 0.621. \quad (1)$$

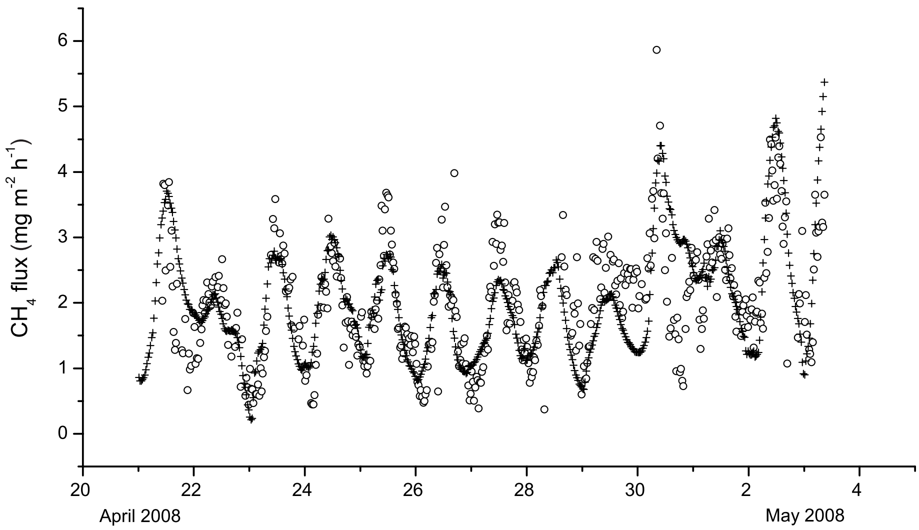

Fig. 3. Diurnal fluctuations in high-resolution CH_4 flux measurements (○) and modelled time series (+) based on reduced major axis regression using surface temperature as a predictor. The time axis is in UTC.

The modelled fluxes were usually underestimated during the day and overestimated at night.

From 21 to 25 April, the measured CH_4 flux was also well correlated with friction velocity (u^*) $r = 0.66$. When u^* was added as a second parameter to T_{sur} from 21 to 25 April, the model performance increased significantly ($R^2{}_{adj} = 0.72$ compared to $r^2{}_{adj} = 0.58$ with T_{sur} only, for these particular days). The equation describing this relationship was

$$F_{CH4} = 0.664 + 3.192\,u^* + 0.197\,T_{sur};\ \mathrm{RMSE} = 0.414. \quad (2)$$

In addition to controls by surface temperature and wind speed, changes in wind direction could also lead to changes in measured flux. At times, wind direction was changing over very short time periods, and spatial differences in the CH_4 flux were observed. For example, on 29 April, the CH_4 flux was increasing, before apparent thaw of the ice layer and an increase in wind speed. On that day, in the morning, the wind direction changed relatively fast from the SE minerogenic depression through S-SW, where more hummocks were present, compared to the minerogenic part in the SE. During the rest of the day, the wind was coming from a relatively narrow region ($\sim 282° \pm 43°$, NW) where the water-logged depression was situated. Wind speed was relatively stable during the day and lower than during the previous days (Fig. 2), and the peak in CH_4 emission as in previous days was not observed (Fig. 3). From 21 to 25 April, the wind direction was changing more or less diurnally from $\sim 150°$ (SE, minerogenic depression) at night, to SW (minerogenic fen) during the day. However, from 26 to 28 April, the wind direction was in a rather narrow range from $226° \pm 18°$ (SW), where the changes in surface coverage are small (Fig. 1), but still strong diurnal variations were observed on these days.

4. Discussion

At our study site, we observed strong diurnal variations of CH_4 fluxes during the early spring period. Diurnal variations of CH_4 fluxes were previously described in different studies (Mikkelä et al., 1995; Thomas et al., 1996; Koch et al., 2007) however, they were referring to controls of diurnal variations during the growing season. During the snow-thaw period analyzed in this study, the ecological conditions are fundamentally different: active vegetation cover is not present, thus no root exudation can fuel CH_4 production, nor can plant-mediated gas transport lead to any significant release of CH_4. It is possible that some plant-mediated transport still exists, especially through old stalks. However, efflux is nearly exclusively by diffusion across the water-air boundary layer (Heyer et al., 2002) and by ebullition (Hargreaves et al., 2001; Tokida et al., 2007). When considering diffusion as the main way of transport, there should be no diurnal peaks in CH_4 flux due to slow (10^{-5} cm^2 s^{-1}) diffusion of gases in water (close to that of peat) (Clymo and Pearce, 1995). However, transport by diffusion can be affected by atmospheric turbulence, especially above water surfaces (Sachs et al., 2008, Wille et al., 2008). In lakes and inundated soils, gas bubbles adhering to surfaces under water could be released during increase of wind speed and could lead to an increased CH_4 flux (Wille et al., 2008). The same authors observed an exponential dependence of CH_4 emission on atmospheric near-surface turbulence at a study site in polygonal tundra, very likely due to high surface coverage of water bodies. Similarly, Hargreaves et al. (2001) found that turbulent eddies interacting with the vegetation can cause increased efflux of CH_4 by ebullition. They found a short-term relationship between CH_4 flux and momentum flux represented by near-surface turbulence. In our study, the correlation with friction velocity was significant only during the period

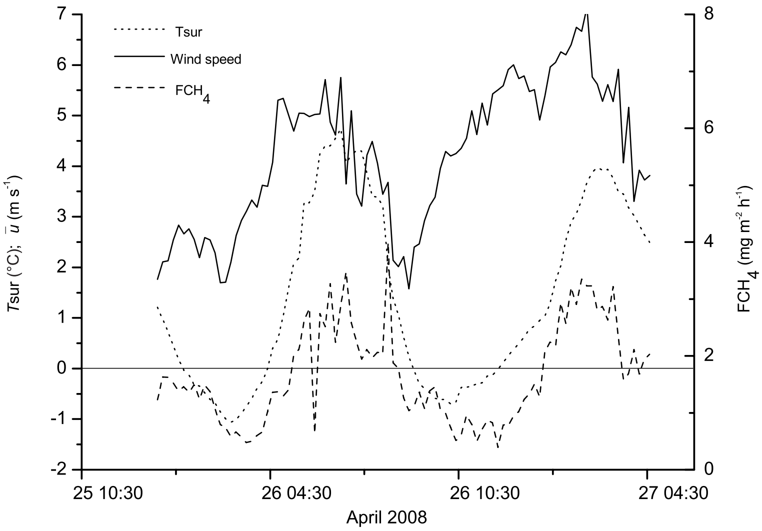

Fig. 4. An increase in wind speed (solid line) did not cause an increase in CH_4 flux (dashed line) when the surface temperature (dotted line) fell below zero and the surface was frozen (see the zero line of surface temperature in the figure). The increase in CH_4 flux follows only after the increase of surface temperature. Time on x-axis is in UTC.

from 21 to 25 April. This might be due to the fact that during this period, water was covering most of the peat surface, and the turbulent mixing could be important to release gas bubbles adhering below the water surface.

During the period with strong diurnal variations of CH_4 fluxes, we observed a regular freezing of the top peat and water layers at night. We hypothesize that this frozen layer acted as a barrier to CH_4 efflux and might lead to a layer of peat in which CH_4 concentrations increase during night. During the course of the day, as air and surface temperature increase, the ice layer successively melts, and CH_4 trapped under the ice is released, also through mixing of the upper part of the water or peat surface, resulting in increased measured CH_4 flux (Fig. 4). Tokida et al. (2007) suggested that high CH_4 concentrations might be caused by rising CH_4 bubbles from deeper layers and their containment under the ice and in the ice by forming ice bubbles. When the surface and water were frozen even a strong increase in wind speed did not have an effect on CH_4 flux (Figs 4 and 5). This might explain the weak relationship of CH_4 flux and u^* after the 25 April, when the night surface temperatures were lower than in the previous days. Thus, the ice layer might have persisted longer into the day. Still, after the melting of the ice layer, turbulent mixing could help to release CH_4. In addition, another factor explaining the weak relationship with friction velocity besides longer persistence of the ice layer during the time after 25 April could be the general decline of the WT, which seems to minimize

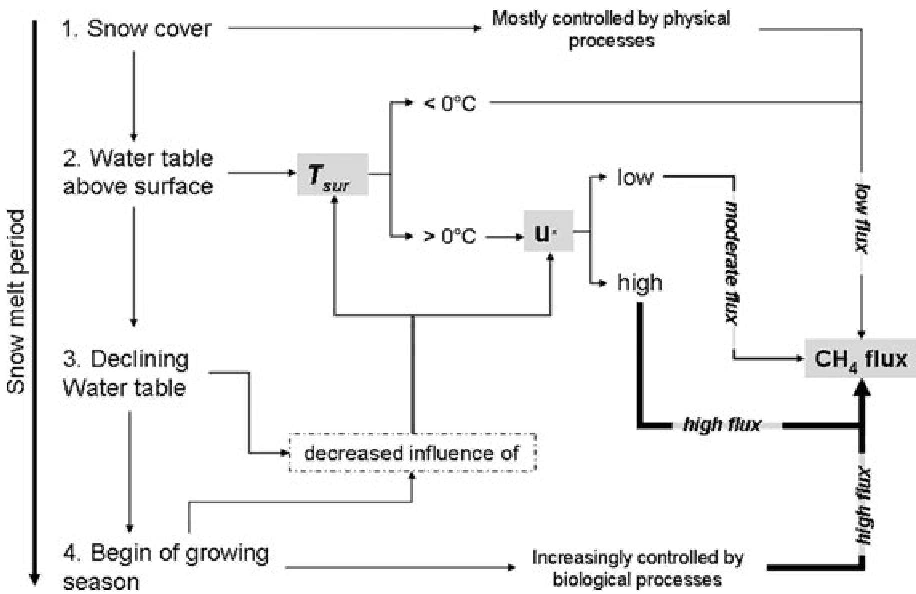

Fig. 5. Conceptual model (flowchart) of the strength in CH_4 flux and its cascade of controlling variables during the four phases (1–4) of the snowmelt period. Most important parameters are surface temperature (T_{sur}) and friction velocity (u^*) (near-surface turbulence), but changes in wind direction and thus source area (not shown here) can also influence the measured CH_4 flux.

the potential effect of turbulent mixing and subsequent increase of CH_4 fluxes (Fig. 4). The factor of changing source area seems to be important on some days; however, it is difficult to consider it without the other controls mentioned earlier. From 21 to 25 April, the source area was changing from the SE at night, where higher WT in combination with low wind speed could be responsible for lower night flux, to SW during the day (minerogenic fen with more hummocks), where higher fluxes could be expected due to higher variability in the surface coverage and the lower WT. However, the following period, 26–28 April, was characterized by winds coming from a narrow region in the SW, similar to the wind direction where the peak CH_4 efflux of previous days was measured. Even with very little variation in the source area, strong diurnal variations have been observed which were apparently not caused by a varying source area, but probably due to factors described earlier. Still, after 25 April, the change of the source area to the minerogenic fen, where more hummocks are present, could be an additional explanation for the decreasing influence of near-surface turbulence.

Evidence of diurnal variation caused by environmental conditions in the early spring might have important implications when the efflux is studied by other methods, for example, closed chambers. In such cases, sampling during the day and extrapolation of results from that one point in time might overestimate early spring fluxes if the mechanism of freezing and thawing as presented in this study is overlooked. In addition, the use of chamber can limit turbulence and thus turbulence-driven efflux as observed in this study, and as a result underestimate CH_4 efflux.

To summarize our findings so far and to fuel further investigation into these phenomena, we propose an idealized flowchart (Fig. 5). The main stages of the snowmelt period (Snow cover, standing water, declining WT and begin of vegetative period) are related to their general flux rates and the possible controlling factors of the measured flux as supported by findings of this study. The highly dynamic spring thaw period seems thus characterized by (1) the transition from low but steady efflux rates mainly controlled by physical properties of the snow cover (Melloh and Crill, 1995) to (2) CH_4 efflux mainly controlled by surface temperature changes, modified by existing turbulence conditions, resulting in diurnally changing CH_4 concentration as found in our study. However, the following transition to the growing season changes the conditions of the environment further leading to higher CH_4 efflux. The high CH_4 efflux during the vegetation period is then mainly driven by increased microbial production, following the increase in soil temperatures and substrate availability (Christensen et al., 2003).

5. Conclusions

In Ust-Pojeg peatland in north-western Russia, diurnal variation in CH_4 flux during the snow-thaw period 2008 occurred as the result of thaw-freeze cycles, enhanced by effects of near-surface turbulence. These two parameters seem to be strong short-term controlling factors for CH_4 release during the dynamic snow-thaw period, when the peatland is in transition from low and steady efflux during winter to the high efflux during the growing season. When water was covering large parts of the peatland surface during this transition period, the increase of CH_4 concentration under the ice layer at night, and subsequent release after thawing during the day enhanced by mixing of water due to increases in wind speed after calm spells resulted in temporarily increased CH_4 flux during the day. Daily peak efflux during the thaw periods reached values of $>3\,\mathrm{mg\,m^{-2}\,h^{-1}}$ in the early afternoon compared to an average of $\sim 0.8\,\mathrm{mg\,m^{-2}\,h^{-1}}$ during nights and $\sim 0.5\,\mathrm{mg\,m^{-2}\,h^{-1}}$ before the snowmelt started. Apparently, during the highly dynamic snow-thaw period, several interactive physical factors influence the gas transport processes and control CH_4 efflux, before other (biological and physical) controls take over in the vegetation period.

6. Acknowledgments

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