Modelling of growing season methane fluxes in a high-Arctic wet tundra ecosystem 1997–2010 using in situ and high-resolution satellite data

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ABSTRACT

Methane (CH4) fluxes 1997–2010 were studied by combining remotely sensed normalised difference water index (NDWI) with in situ CH4 fluxes from Rylekærøren, a high-Arctic wet tundra ecosystem in the Zackenberg valley, north-eastern Greenland. In situ CH4 fluxes were measured using the closed-chamber technique. Regression models between in situ CH4 fluxes and environmental variables [soil temperature (Tsoil), water table depth (WtD) and active layer (AL) thickness] were established for different temporal and spatial scales. The relationship between in situ WtD and remotely sensed NDWI was also studied. The regression models were combined and evaluated against in situ CH4 fluxes. The models including NDWI as the input data performed on average slightly better [root mean square error (RMSE) = 1.56] than the models without NDWI (RMSE = 1.67), and they were better in reproducing CH4 flux variability. The CH4 flux model that performed the best included exponential relationships against temporal variation in Tsoil and AL, an exponential relationship against spatial variation in WtD and a linear relationship between WtD and remotely sensed NDWI (RMSE = 1.50). There were no trends in modelled CH4 flux budgets between 1997 and 2010. Hence, during this period there were no trends in the soil temperature at 10 cm depth and NDWI.

Keywords: NDWI, methane, Arctic, Landsat, climate change

1. Introduction

High-latitude ecosystems are identified to be vulnerable to climate change and there is substantial evidence for effects of climate warming in the Arctic (Christensen et al., 2004; Johansson et al., 2006; Tarnocai, 2006) leading to permafrost degradation, melting of snow, glaciers and sea ice, lengthening of the growing season, a shift in plant species composition, increased emissions of methane (CH4) and carbon dioxide (CO2) and increased plant productivity (Oechel et al., 1993; Svensson et al., 1999; Serreze et al., 2000; Christensen et al., 2004; Malmer et al., 2005; Johansson et al., 2006; Tarnocai, 2006). In the centuries to come, Arctic areas are projected to experience more pronounced changes in temperature, precipitation and length of the growing season than the rest of the world (ACIA, 2005; IPCC, 2007). These climatic variables have strong effects on the land–atmosphere exchange of CH4 and CO2, indicating risks of positive feedback mechanisms (e.g. Christensen et al., 2004; Johansson et al., 2006). Northern wet tundra ecosystems play a key role in controlling the terrestrial carbon cycle, and approximately 50% of the global soil organic carbon is today stored in the northern permafrost regions (Smith et al., 2004;
McGuire et al., 2009; Tarnocai et al., 2009). Wet tundra ecosystems are also ideal sites for CH$_4$ production, and the atmospheric input of CH$_4$ from northern latitude wetlands accounts for about 25% of the total natural CH$_4$ sources globally (Schlesinger, 1997). Excluding the effect of water vapour, CH$_4$ has contributed to approximately 22% of the greenhouse effect during the past 150 yr (IPCC, 2007). The land–atmosphere exchange of CH$_4$ is the sum of the methanogenesis in the wet anaerobic part of the soil and the methanotrophy in the aerated upper part of the soil. The net CH$_4$ flux is highly dependent on water table depth (WtD), soil temperature, ecosystem productivity, species composition, and for permafrost environments date of snowmelt and active layer (AL) thickness (see Appendix A.1 for abbreviations and symbols; Bubier and Moore, 1994; Friberg et al., 2000; Mastepanov, 2010). As a consequence of climate change, changes in vegetation composition and site-specific variations in emissions of CH$_4$ and CO$_2$ have already been reported from sub-Arctic and Arctic areas (Oechel et al., 1993; Svensson et al., 1999; Christensen et al., 2004; Malmer et al., 2005; Johansson et al., 2006; Thompson et al., 2006).

The CH$_4$ fluxes in Arctic ecosystems are not only varying in the temporal domain but there is also a strong spatial component. For example, several studies have shown a correlation between the spatial variation in WtD and the CH$_4$ fluxes (Hargreaves and Fowler, 1998; Huttunen et al., 2003; Wille et al., 2008). For accurate assessments of landscape-level CH$_4$ fluxes, it is necessary to estimate its spatial variation. Assessing landscape-level emissions using manual field-based measurements is time consuming, and remote sensing tools can be used. Optical remote sensing uses measures of surface reflectance to model and map ground characteristics on landscape to global scales. Reflectance within the short-wave infrared (SWIR) wavelengths is known to be highly sensitive to water content of the ground and atmosphere (Lillesand et al., 2008). Variation in reflectance in the SWIR bands is also affected by the internal leaf structure, leaf dry matter content, soil mineral composition and organic matter content (Whiting et al., 2004; de Alwis et al., 2007). Consequently, the SWIR bands alone are not appropriate for estimating hydrological conditions. The near-infrared (NIR) bands are affected by the same ground properties as the SWIR bands, except that the absorption by vegetation liquid water is negligible. Gao (1996) hereby proposed a vegetation index, the normalised difference water index (NDWI), using NIR and SWIR bands to estimate vegetation liquid water. The NDWI has also been applied for estimates of water stress on gross primary production, plant phenology, land cover classification and soil water saturation (Boles et al., 2004; Xiao et al., 2004; Delbart et al., 2005; de Alwis et al., 2007).

The primary aim of this study is to investigate the applicability of combining in situ and high-resolution satellite data for modelling growing season CH$_4$ fluxes. The drivers of CH$_4$ fluxes at different temporal and spatial scales were investigated by relating in situ CH$_4$ fluxes to environmental variables using regression models. The resultant models were used to scale-up the in situ CH$_4$ fluxes to landscape and inter-annual scales. For the up-scaling, the relationship between in situ soil hydrology and remotely sensed measures of ecosystem moisture content (NDWI) was also studied. The final aim is to investigate trends in growing season CH$_4$ fluxes, 1997–2010, in a high-Arctic wet tundra ecosystem in north-eastern Greenland.

2. Materials and methods

2.1. Site description

The study was done in Rylekærere (dunlin fens) in the Zackenberg valley (74°28’N 20°34’W), located in the Northeast Greenland National Park. Rylekærere is a patterned wet tundra ecosystem characterised by alternating sequences with high, dry heath areas and low, wet fen areas. These sequences are mainly orientated in strings perpendicular to the hydrologic flow, which goes from NE to SW. The Zackenberg valley is subject to a relatively mild climate for the high-Arctic zone with an average temperature of 5.8°C in the warmest month of the year (July) and mean annual temperature of −9°C (Hansen et al., 2008). The Zackenberg valley is underlain by continuous permafrost and the AL thickness ranges from 0.5 to 1.0 m. The dominant plant communities in the Zackenberg valley are continuous fen (flat areas dominated by Eriophorum scheuchzeri, Carex stans and Dupontia psilosantha), and hummocky fen (hummocks dominated by Eriophorum triste, Salix arctica and Arctagrostis latifolia), grassland (dominated by A. latifolia, E. triste and Alopecurus alpinus), S. arctica snowbed, Cassiope tetragona heath, Dryas octopetala heath and Vaccinium uliginosum heath (Fig. 1); which are distributed spatially due to topography, hydrology and soil type (Elberling et al., 2008). The moss species at the site was dominated by Tomenmyxnum, Scorpidiun, Autacornium and Drepanocladus. Since 1995, extensive ecological, biogeographic, climatic and hydrological research and monitoring have been carried out in the Zackenberg research area (Meltote and Rasch, 2008). The Rylekærere area in this study is the 1.4 km$^2$ area covered by the vegetation composition map in Fig. 1.
Fig. 1. The Zackenberg valley and the investigation area surrounding the research station (ZERO). The field inventory map of the dominant plant communities estimated in the Rylekærene study site is superimposed over the area. The vegetation map is the studied area referred to as Rylekærene throughout the text. The red dot on the Greenland map is the location of Zackenberg. The Footprint areas are the average 80% cumulative flux distances of the two towers.
2.2. In situ measurements

2.2.1. Chamber measurements of CH$_4$ fluxes. In 2007, a site in the centre of the Rylekærere was chosen so as to encompass the main plant communities dominating the fen within a reasonably small area (~600 m$^2$) (Fig. 1). A total of 55 plots were randomly distributed within the different plant communities; five plots each in the C. tetragona heath, Dryas octopetala heath, V. uliginosum heath and Salix arctica snowbed, 10 plots each in hummocky fen and grassland and 15 plots in continuous fen. CH$_4$ fluxes were measured in each of the plots using the closed-chamber technique (Livingston and Hutchinson, 1995). A laser off-axis integrated cavity output spectroscopy analyser (LGR, DLT200 Fast Methane Analyzer, Los Gatos Research, USA) was used to measure chamber concentration of CH$_4$. Measurements were performed 11 times on the 55 plots between 30 June and 4 August 2007. To avoid bias due to measurements at different times of the day in different plant communities, measurements were distributed over the day, such that every second measurement in an individual plots was performed during the morning after 10 a.m., and every second time during the afternoon no later than 6 p.m.

The chamber was a transparent Plexiglas cube of 0.3 m height and a ground area of 0.34 m$^2$. The outlet and inlet for gases were located on one of the chamber sides, 0.15 and 0.25 m above the ground, respectively. Two small fans were located in the upper part of the chamber to ensure proper mixing of the chamber headspace and representative sampling. The chamber was vented to minimise artefacts due to changes in pressure or temperature (Livingston and Hutchinson, 1995). Care was taken to avoid induction of an efflux of CH$_4$ as the chamber was placed on the soil. Collars inserted in the ground were not used during the measurements, but to ensure a proper seal between the chamber and the soil, the chamber was placed in ~2 cm notches inserting the chamber into the ground. The notches were constructed in the start of the growing season, before the measurements started.

Methane concentrations in the chamber were measured every second over the course of 3 min. Concentrations were first measured under daylight conditions, then in the dark, by covering the chamber with a lightproof hood. The chamber was ventilated for 1.5 min between the measurements. Ordinary least-square linear functions were fitted to the concentration change in the chamber over the measurement cycle. The slope of the line was used to calculate the CH$_4$ fluxes according to Livingston and Hutchinson (1995). Fifteen percent of the chamber measurements were removed due to problems in chamber installation, causing initial ebullition (peak in CH$_4$ concentration after the chamber installation) or leakage (noisy time series without linear trends in CH$_4$ concentration).

2.2.2. Environmental variables. Soil temperature at 10 cm depth ($T_{10}$), WtD (centimetres below moss surface) (for the fen communities) and AL (centimetres below moss surface) was measured simultaneously with the chamber-based CH$_4$ flux measurements between 30 June and 4 August 2007. Water table depth was measured in small holes in close proximity to the chamber measurement plots, and AL was measured with a metal rod driven in to the ground until it reached the top of the permafrost. Soil temperature at 10 cm depth was measured with a 125 mm digital temperature probe (Viking, Eskilstuna, Sweden). The 10 cm depth was chosen as a good proxy of the temperature of the depth of maximum potential CH$_4$ production at the site which is between 5 and 15 cm (Joabsson and Christensen, 2001).

Soil temperature at 10 cm depth has been continuously measured at the climate station (C1) between 1996–2004 and 2006–2010 (Jensen and Rasch, 2011), from July 2007 to October 2010 at monitoring site 1 (Mastepanov, 2010) and in July–August 2000 at monitoring site 2 (Fig. 1; Joabsson and Christensen, 2001). Water table depth was measured in small holes in the centre of Rylekærere at 26, 1 and 5 sites during the growing seasons of 2008, 2009 and 2010, respectively. In addition, WtD was measured at monitoring sites 2 and 1 during the growing seasons of 2000 and 2007–2010, respectively (Joabsson and Christensen, 2001; Mastepanov, 2010). In 1997, Friborg et al. (2000) measured WtD at the 1997 tower site (Fig. 1). AL thickness was measured at monitoring site 1 in 2007, 2008 and 2009, and at monitoring site 2 in 2000 (Joabsson and Christensen, 2001; Mastepanov, 2010). In 1997, Friborg et al. (2000) measured AL at the 1997 tower site (Fig. 1).

Following Tamstorf et al. (2007), the growing season was assumed to extend from the day of year (DOY) for snow melt to the first of two consecutive days with a soil temperature at 2.5 cm of 0°C or below. Soil temperature data at 2.5 cm depth were taken from C1 (Jensen and Rasch, 2011). Snow depths have been monitored 1998–2010 at C1 (Jensen and Rasch, 2011). The bottom of the Zackenberg valley is relatively flat, and the conditions at C1 are hereby also representative of the studied Rylekærere area. The DOY when snow depths decreased below 10 cm at C1 was used as a proxy for DOY of snowmelt. For 1997, modelled snow cover in the Zackenberg valley from Buus-Hinkler et al. (2006) was used to estimate DOY of snowmelt (Tagesson et al., 2012a).

2.3. Remote sensing data

Data from the moderate resolution imaging spectroradiometer (MODIS) were used in a pre-analysis for determining the average peak season of the NDWI during...
2000–2010. Single grid cell subsets (grid size: 500 m × 500 m) of the growing season 8-d surface reflectance composites were extracted from the MODIS/Terra L3 collection (MOD09A1) from March 2000 to October 2010 (ORNL DAAC, 2010). The grid cell chosen was from the centre of the Rylekærere. The reflectance data were filtered based on MODIS QC criteria. The NDWI was calculated using surface reflectance data from MODIS according to the following:

\[ \text{NDWI} = \frac{\rho_{\text{NIR}} - \rho_{\text{SWIR}}}{\rho_{\text{NIR}} + \rho_{\text{SWIR}}} \]  

where \( \rho_{\text{NIR}} \) is the reflectance in the NIR band, and \( \rho_{\text{SWIR}} \) is the reflectance in the SWIR band. Average values and standard deviations (SDs) for the period 2000–2010 were calculated for each 8 d period from the start until the end of the growing season. Based on the MODIS growing season NDWI, the period between 38 and 55 d after DOY of snowmelt was chosen to represent the NDWI peak season (Fig. 2). The MODIS-based NDWI was never used in the actual modelling of CH4 fluxes. Data of higher spatial resolution were required for the actual analysis, Landsat TM and ETM+ images (grid size: 30 m × 30 m) obtained at the NDWI peak seasons of 1997–2010 were chosen for the analysis (Table 1). The NDWI could be affected by precipitation; hence, images with precipitation within 3 d before the DOY of the satellite images were rejected. Images of the chosen satellite are given in Table 1.

To compare images between dates and years, all Landsat imagery was converted into reflectance and atmospheric and terrain corrections were performed with ATCOR 3 (version 6.2; Richer, 2005). This method uses look-up tables derived using the Modtran® 4 radiative transfer code covering a wide range of weather conditions, sun angles and ground elevations. Finally, NDWI based on the Landsat data in Table 1 was calculated according to eq. (1).

2.4. Data analysis

2.4.1. Correspondence between soil hydrology and NDWI. The WtD measured at the DOY of the satellite images in Table 1 was extracted from the WtD time series for each plot and year. The extracted WtD data were averaged for each satellite pixel. Water table depth measurements within two satellite pixels were removed from the analysis, as these pixels covered the edge of the fen and hereby had large fractions of both heath and fen areas. The WtD were measured only in the fen area (a few metres into the fen) and were not representative of the combined heath/fen-covered satellite pixel. The NDWI do not measure the actual soil hydrology, but rather the effect of soil hydrology on the ground vegetation. The soil hydrology were therefore categorised into seven categories based on our WtD data (WtDcat); > 0 cm (category 0), 0 to < 1.0 cm (category 1), 1 to < 2.0 cm (category 2), 2.0 to < 3.5 (category 3), 3.5 to < 5.0 cm (category 4), 5.0 to < 8.0 cm (category 5) and > 8.0 cm (category 6). The NDWI was averaged for each WtDcat. A linear regression between WtDcat and average NDWI was fitted as follows:

\[ \text{WtD}_{\text{cat}} = u + w \times \text{NDWI} \]  

where \( u \) is the intercept and \( w \) is the slope of the linear regression (for results, see Section 3.1.2). A reduced
variances among groups to test if the in situ CH4 fluxes differed between the plant communities and between CH4 fluxes. We performed repeated-measures ANOVA, with a Tukey’s post hoc test assuming equal environmental variables.

We obtained the DOY of 10 cm snow depth based on snow coverage by Buus-Hinkler et al. (2006). In 2009, the snow depth was by far the shallowest on record and peaked at 17 cm. It was therefore below 10 cm already DOY 136 according to snow depth measurements at C1. In the central parts of the fen, it was visually seen to melt DOY 152.

The chamber-based CH4 fluxes were averaged for each of the 11 measurement occasions for both continuous and hummocky fen. The T10 and WtD measured at monitoring station 1 were averaged for the same 11 occasions. To determine which of the measured environmental variables that best described the temporal variation in CH4 fluxes and to find model parameters for the subsequent CH4 flux modelling, simple and multiple ordinary least-square linear and exponential regression functions were fitted between the averaged CH4 fluxes and the averaged T10, WtD and AL.

In addition, the spatial relationship between environmental variables and CH4 fluxes was investigated. The CH4 fluxes and T10 measured over the growing season were averaged for each measurement plot. The relationship between spatial variation of CH4 fluxes and WtD and T10 was analysed separately for continuous and hummocky fen by fitting linear and exponential least-square regression functions between plot-averaged CH4 fluxes on average T10 measured in the vicinity of each plot, and WtD measured at the day of the satellite image 2007 (DOY 210, 29 July).

Day of year (DOY) when the images were obtained is also included. The DOY of 10 cm snow depth for the different years, which was used as start of the growing season, is also given.

The 10 cm snow depth based on snow coverage by Buus-Hinkler et al. (2006). In 2009, the snow depth was by far the shallowest on record and peaked at 17 cm. It was therefore below 10 cm already DOY 136 according to snow depth measurements at C1. In the central parts of the fen, it was visually seen to melt DOY 152.

Images taken when the Scan Line Corrector on Landsat 7 was broken.

Table 1. The different sensors recording the Landsat images that were used in the analysis

| Year | Satellite sensor | DOY of Landsat image | DOY with 10 cm snow depth |
|------|------------------|----------------------|--------------------------|
| 1997 | Landsat 5 TM     | 222                  | 170                      |
| 2000 | Landsat 7 ETM+   | 204                  | 165                      |
| 2002 | Landsat 7 ETM+   | 214                  | 171                      |
| 2007 | Landsat 7 ETM+   | 210                  | 159                      |
| 2008 | Landsat 7 ETM+   | 222                  | 175                      |
| 2009 | Landsat 7 ETM+   | 199                  | 152                      |
| 2010 | Landsat 7 ETM+   | 219                  | 167                      |

Major-axis linear regression was chosen as errors were assumed in both variables. The normality assumptions for residuals were checked throughout the study using the Kolmogorov–Smirnov test. The statistics was regarded as significant at a p-value threshold of 0.05.

2.4.2. Correspondence between CH4 fluxes and environmental variables. We performed repeated-measures ANOVA, with a Tukey’s post hoc test assuming equal variances among groups to test if the in situ CH4 fluxes differed between the plant communities and between CH4 flux for light and dark conditions.

The chamber-based CH4 fluxes were averaged for each of the 11 measurement occasions for both continuous and hummocky fen. The T10 and WtD measured at monitoring station 1 were averaged for the same 11 occasions. To determine which of the measured environmental variables that best described the temporal variation in CH4 fluxes and to find model parameters for the subsequent CH4 flux modelling, simple and multiple ordinary least-square linear and exponential regression functions were fitted between the averaged CH4 fluxes and the averaged T10, WtD and AL.

In addition, the spatial relationship between environmental variables and CH4 fluxes was investigated. The CH4 fluxes and T10 measured over the growing season were averaged for each measurement plot. The relationship between spatial variation of CH4 fluxes and WtD and T10 was analysed separately for continuous and hummocky fen by fitting linear and exponential least-square regression functions between plot-averaged CH4 fluxes on average T10 measured in the vicinity of each plot, and WtD measured at the day of the satellite image 2007 (DOY 210, 29 July).

2.5. The CH4 flux models

2.5.1. Models estimating temporal variation of CH4 flux. Based on the outcome of the correlations previously described under Section 2.4.2 (for results see Section 3.1.1), four regression models were constructed from the fitted functions for further analysis. The models differed in the functional form and in choice of predictor variables included (T10, WtD, AL or a combination of these).

Workflow of the model development and evaluation is visualised in Fig. 3. The models were parameterised for continuous and hummocky fen using non-linear least-square regression analysis in the software SPSS Statistics Version 19. Model 1 represents CH4 flux (FCH4) as an exponential function of T10 as follows:

\[ F_{\text{CH4}} = a \times e^{(c \times T_{10})} \]  \hspace{1cm} (3)

where \( a \) is the intercept of the curve and \( c \) is the growth constant.

Model 2 was based on eq. (3), with the addition of a term to represent the effect of AL, as parameterised by Friberg et al. (2000) as follows:

\[ F_{\text{CH4}} = a \times e^{(c \times T_{10})} \times \left( \frac{AL}{AL_{\text{max}}} \right)^d \]  \hspace{1cm} (4)

where \( AL_{\text{max}} \) is the peak AL measured during the growing season.

Model 3 expresses the CH4 flux as a linear function of WtD and an exponential function of T10 as follows:

\[ F_{\text{CH4}} = (a + b \times WtD) \times e^{(c \times T_{10})} \]  \hspace{1cm} (5)

where \( a, b \) and \( c \) are fitted parameters.

Model 4 adds the effect of AL, following Friberg et al. (2000), to eq. (5) as follows:

\[ F_{\text{CH4}} = (a + b \times WtD) \times e^{(c \times T_{10})} \times \left( \frac{AL}{AL_{\text{max}}} \right)^d \]  \hspace{1cm} (6)

Models 1–4 estimate the temporal variation in CH4 flux over the growing seasons.

2.5.2. The spatial extrapolation of the modelled CH4 fluxes. To estimate the CH4 flux for the entire Rylekærene area, models 1–4 were spatially extrapolated on all pixels with continuous and hummocky fen areas in the vegetation map (Fig. 1). The remaining pixels containing grassland, heath, gravel and water were given a modelled CH4 flux...
value of zero since no CH4 fluxes were detected from these areas at any time during the growing season (for results see Section 3.1.1). The subscript 'nosat' is used hereinafter to refer to these models, as they do not include satellite data as input data.

In addition, the modelled CH4 fluxes from Modelnosat1-4 were spatially extrapolated over the studied Rylekærene area based on remotely sensed NDWI. To estimate the contribution in CH4 flux of an individual plot in comparison to the average CH4 flux from all plots (hereafter referred to as $F_{\text{CH4,frac}}$), the plot-averaged CH4 fluxes ($F_{\text{CH4,plot}}$) were divided by the average CH4 flux for all plots ($F_{\text{CH4,all}}$), treating the continuous and hummocky fen data sets separately as follows:

$$F_{\text{CH4,frac}} = \frac{F_{\text{CH4,plot}}}{F_{\text{CH4,all}}}$$  \(7\)

This gave a fraction of how the CH4 fluxes vary spatially in relationship to the average. The measured WtD at DOY 210 (29 July) 2007 at each chamber measurement point was assigned to a WtDcat category, as described in

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**Fig. 3.** Workflow for the model development and the model evaluation. The white boxes are steps in the work process of the model development or the model evaluation. The grey boxes are input data or equations going into the models. The thick arrows indicate steps in the work process, whereas thin arrows indicate input. The final results of the model evaluation were the root mean square error, the model-in situ ratio and the goodness-of-fit given by a linear regression equation.
Section 2.4.1. An exponential regression of $F_{\text{CH}_4, \text{frac}}$ against plot WtD$_{\text{cat}}$ was thereafter fitted, for both continuous and hummocky fen as follows:

$$F_{\text{CH}_4, \text{frac}} = k \times e^{WtD_{\text{cat}} \times l}$$

(8)

where $k$ is the intercept of the exponential curve and $l$ is the growth constant. This provided a relationship to estimate the relative CH$_4$ flux at any point against the average, as a function of the WtD$_{\text{cat}}$ at that point.

The previously derived WtD$_{\text{cat}}$-NDWI relationship [eq. (2), Section 2.4.1] gives satellite-based WtD$_{\text{cat}}$ images. Applying eq. (8) to these WtD$_{\text{cat}}$ images create $F_{\text{CH}_4, \text{frac}}$ images. The $F_{\text{CH}_4, \text{frac}}$ images can subsequently be multiplied with the CH$_4$ fluxes modelled with the Model$_{\text{nosat}}$ 1–4, and the CH$_4$ fluxes for each satellite pixel in the entire Rylekærene are hereby estimated as follows:

$$F_{\text{CH}_4} = (k \times e^{u + w \times NDWI}) \times (\text{Eqs. 3–6})$$

(9)

where $k$ and $l$ are the constants from eq. (8), and $u$ and $w$ are constants from eq. (2). The first term of eq. (9) on the right-hand side, represents the spatial variation in relationship to the average of the area, whereas the second term on the right-hand side [eqs. (3–6)] of eq. (9), represents the temporal variation in CH$_4$ flux. These models are named Model$_{\text{sat}}$ 1–4 hereinafter, and the subscript ‘sat’ is used as these models include satellite-based NDWI.

### 2.6. Evaluation of the models

#### 2.6.1. In situ CH$_4$ flux data used for model evaluation.

For the evaluation of the regression models, a number of different data sets were used. During the growing seasons 2008 and 2009, fen-scale CH$_4$ fluxes were measured by combining the eddy covariance technique with atmospheric gradients and the K-theory (Tagesson et al., 2012b). We also used data from Friiborg et al. (2000), who similarly measured fen-scale CH$_4$ fluxes during the growing season of 1997, with the eddy covariance technique. The footprints of the towers were estimated with a footprint model developed by Hsieh et al. (2000) based on the Obukhov lengths, given by sonic anemometer data, the measurement heights and the surface roughness length. The measurement height of the EC system was 2.7 m in 1997. For 2008 and 2009, measurement heights in the footprint model were set to the arithmetic (1.73 m) and the geometric (1.39 m) mean of the measurement heights of the concentration gradient, for stable and unstable conditions, respectively (Horst, 1999). Momentum roughness length was set to 0.01 m (Wieringa, 1993; Mölder and Kellner, 2002). The flux footprint model gives a footprint-weighed function estimating the relative contribution of the different parts of the tower footprint. The average 80% cumulative flux distances of the two towers are shown in Fig. 1. Finally, we used closed-chamber measurements of CH$_4$ fluxes from the study of Joabsson and Christensen (2001) covering six continuous fen plots at monitoring site 2 during the growing season of 2000 (Fig. 1).

#### 2.6.2. Evaluation of temporally and spatially extrapolated CH$_4$ fluxes. Model$_{\text{nosat}}$ 1–4 and Model$_{\text{sat}}$ 1–4 were evaluated against the in situ CH$_4$ fluxes for 1997, 2000 and 2008–2009. The $T_{10}$, WtD and AL observations for 1997, 2000 and 2008–2009 (Table 2) were used as the model input data. Monitoring sites 1 and 2 are 45 m apart, and situated along the same edge of the fen. It was therefore assumed that the environmental variables were similar between the two sites. In 1997, WtD was not measured at either of the monitoring sites 1 and 2, and Model$_{\text{nosat}}$ 3–4 and Model$_{\text{sat}}$ 3–4 were thus not applied for this year.

Model$_{\text{nosat}}$ 1–4 were applied on all pixels with continuous and hummocky fen areas in the vegetation map (Fig. 1) separately for 1997, 2000 and 2008–2009. The remaining pixels containing grassland, heath, gravel and water were given a modelled CH$_4$ flux value of zero.

| Year | $T_{10}$ | WtD | AL |
|------|---------|-----|----|
| 1997 | M1$^a$  | –   | T1997 |
| 2000 | M2$^b$  | M2  | M2 |
| 2002 | M1$^c$  | –   | M1$^c$ |
| 2007 | M1$^d$  | M1  | M1 |
| 2008 | M1     | M1  | M1 |
| 2009 | M1     | M1  | M1 |
| 2010 | M1     | –   | M1 |

$T_{10}$ is the soil temperature at 10 cm depth, WtD is the water table depth and AL is the active layer thickness. Gaps in the data series were filled by linear interpolation. The ‘-’ either means that no measurements were done, or that they were not necessary in the modelling process. M1 is the monitoring site 1, M2 is the monitoring site 2 and T1997 is the Tower site 1997 (Fig. 1).

$^a$Model$_{\text{sat}}$ modelled with a linear regression fitted between $T_{10}$ at monitoring site 1 d 1–57 of the growing seasons 2007, 2008 and 2009 and $T_{10}$ at C1 ($R^2 = 0.47, n = 4147$).

$^b$Model$_{\text{sat}}$ was measured from the 8 July 2000. At the start of the growing season, a linear regression fitted between hourly averaged $T_{10}$ at monitoring site 2 in 2000 and hourly $T_{10}$ at C1 ($R^2 = 0.89, n = 1062$) was used.

$^c$Model$_{\text{sat}}$ modelled with a linear regression fitted between AL at monitoring site 1 of the growing seasons 2007, 2008 and 2009 and AL at ZEROCALM1 (Jensen and Rasch, 2011) ($R^2 = 0.96, n = 23$).

$^d$Model$_{\text{sat}}$ was measured from the 4 July 2007. At the start of the growing season, a linear regression fitted between hourly values of $T_{10}$ at monitoring site 1 and C1 ($R^2 = 0.80, n = 1531$) for the growing season 2007, was used.
For Model_{sat} 1–4, the CH4 fluxes from Model_{nosat} 1–4 were used for the second term of eq. (9). For the first term of eq. (9), NDWI estimates of the satellite images from 1997, 2000, 2008 and 2009 in Table 1 were used as input data. Combined, eq. (9) gave the CH4 fluxes for each satellite pixel in the entire Rylekærøene.

The relative contribution of the different parts of the tower footprint was estimated with a footprint-weighed function (Hsieh et al., 2000) (see Section 2.6.1). This relative contribution of the different parts of the tower footprint was taken times the Model_{nosat} 1–4 and Model_{sat} 1–4 maps to estimate the modelled CH4 fluxes for the same areas as measured with the towers.

The CH4 fluxes were modelled for each half-hour that was measured with the micrometeorological measurements 1997 and 2008–2009. For evaluation against the chamber measurements, the CH4 fluxes were modelled for the same point in time as the chamber measurements were conducted. Daily averages were calculated with modelled and in situ CH4 fluxes. Finally, the daily-averaged Model_{nosat} 1–4 and the daily-averaged Model_{sat} 1–4 from the footprint area of the towers were evaluated against the daily-averaged tower-based CH4 fluxes 1997 and 2008–2009 (Friberg et al., 2000; Tagesson et al., 2012b). It was also evaluated against the chamber-based CH4 flux measurements from 2000 at monitoring site 2 (Joabsson and Christensen, 2001). The model-in situ data agreements were quantified as the root mean square error (RMSE), the model-in situ ratio, and by goodness-of-fit when a least-square linear regression was fitted between average modelled CH4 fluxes against the averaged in situ fluxes.

2.7. Growing season CH4 fluxes 1997–2010

Equation (4) parameterised for continuous and hummocky fen was used in eq. (9) to model CH4 fluxes 1997–2010. The T10 and AL data in Table 2 and the NDWI images in Table 1 were used as input data to eq. (9).

Average modelled CH4 fluxes day 1–57 of the growing season were calculated for the entire Rylekærøene area. Only day 1–57 were used due to the results of the model evaluation (see Section 3.2). Accumulated CH4 fluxes day 1–57 of the growing seasons were calculated to estimate a CH4 flux budget for Rylekærøene for the different years. The uncertainties of the models for the different years were estimated by calculating model standard errors (SEs) using the formula for error propagation (see Appendix A.2). In addition, average T10 measured at C1 day 1–57 of the growing season was calculated 1996–2004 and 2007–2010. Maximum MODIS-based NDWI from the peak period of the growing season was extracted for 2000–2010.

3. Results

3.1. The relationships to environmental variables

3.1.1. CH4 flux and environmental variables. In the 2007 chamber flux measurements, no CH4 fluxes were statistically different from zero for the grassland, S. arctica snowbed, C. tetragona heath, Dryas octopetala heath or V. uliginosum heath plots (Table 3). However, on 11% of the heath and S. arctica snowbed measurements we observed negative CH4 fluxes (Table 3). There were significant differences between the CH4 fluxes in continuous and hummocky fen (p < 0.0001). They were therefore treated as two categories in the subsequent data analysis. There were, however, no significant differences between CH4 fluxes measured in dark and light conditions for either continuous (p = 0.965) or hummocky fen (p = 0.998). We therefore chose to combine light and dark measurements in the subsequent data analysis. Average CH4 fluxes measured between 10 a.m. and 6 p.m. during the period 30 June – 4 August 2007 were 9.1 ± 5.3 (± 1 SE) mg CH4 m−2 h−1, and 3.6 ± 2.5 mg CH4 m−2 h−1, for continuous and hummocky fen, respectively.

Table 3. Average (± 1 SD) CH4 fluxes and environmental variables measured between 10 a.m. and 6 p.m. in the period 30 June–4 August 2007, for the different plant communities

| Plant communities | T10 (°C) | WtD (cm) | ALmax (cm) | CH4 flux (mg CH4 m−2 h−1) | Sample size |
|-------------------|----------|----------|------------|--------------------------|-------------|
| Continuous fen    | 7.4 ± 1.3 | −3.4 ± 3.6 | 49 ± 3     | 9.1 ± 5.3                | 154         |
| Hummocky fen      | 7.4 ± 1.3 | −8.2 ± 4.2 | 47 ± 4     | 3.6 ± 2.5                | 108         |
| Grassland         | 6.0 ± 1.3 | −       | 56 ± 8     | 0.1 ± 0.4                | 110         |
| Salix snowbed     | 8.2 ± 2.1 | −       | 78 ± 3     | −0.04 ± 0.04             | 51          |
| Vaccinium Heath   | 7.6 ± 2.3 | −       | 69 ± 5     | −0.02 ± 0.04             | 54          |
| Cassiope heath    | 7.7 ± 1.6 | −       | 74 ± 6     | −0.03 ± 0.03             | 54          |
| Dryas heath       | 8.9 ± 2.1 | −       | 75 ± 5     | −0.03 ± 0.03             | 54          |

The T10 is the average soil temperature at 10 cm depth and WtD is the average water table depth (centimetres below moss surface) measured 21 June–4 August 2007. ALmax is the average active layer thickness (centimetres below moss surface) from the 4 August 2007, when the thickest AL was measured.
Water tables from 30 June –4 August 2007 were on average 3.4 and 8.2 cm below the ground surface for continuous and hummocky fen, respectively. No free-standing water was detected in the ALs of Grassland, S. arctica snowbed, C. tetragona, Dryas octopetala and V. uliginosum heath. The thickest average AL measured on 4 August, ranged from 47 to 78 cm, for the different plant communities (Table 3). Plant communities at elevated and drier locations had a thicker AL than the plant communities in the wetter locations.

There were close relationships between temporal variation in CH4 fluxes and \( T_{10} \) for continuous and hummocky fen. The function with the best correlation was exponential for hummocky fen (Table 4 and Fig. 4a). For continuous fen, the linear and exponential functions were equally well correlated (Table 4 and Fig. 4a). The exponential function was chosen for further analysis, as it is theoretically more correct (e.g. Dunfield et al., 1993). There were also linear correlations with WtD for both continuous and hummocky fen (Table 3 and Fig. 4b). The AL measurements started at \( \sim \)24 cm depth, and we did hereby not measure CH4 fluxes at any shallow AL. The AL increased throughout the growing season whereas CH4 flux decreased in the end of the season, and this resulted in a negative linear correlation between CH4 flux and AL (data not shown). In the subsequent modelling analysis including effects of AL, we therefore apply the parameterisation by Friborg et al. (2000).

3.1.2. The spatial relationships to environmental variables.

There was no correlation between spatial variation in CH4 fluxes and \( T_{10} \), but significant exponential relationships between spatial variation in CH4 fluxes and WtD at the DOY of the satellite image 2007 were found (Fig. 5).

Exponential regression of \( F_{\text{CH4 flux}} \) on plot WtDcat [eq. (8)] gave an \( R^2 \) of 0.61 for continuous fen (\( F_{\text{CH4 flux}} = 1.32 \times e^{-0.82 \times \text{WtD cat}}, n = 15 \)) and 0.49 for hummocky fen (\( F_{\text{CH4 flux}} = 4.74 \times e^{-0.33 \times \text{WtD cat}}, n = 10 \)). There was a significant relationship between in situ measurements of WtDcat and remotely sensed NDWI (Fig. 6).

3.2. Model evaluation

The first 57 d after snowmelt, the in situ CH4 fluxes were generally well described by the models; modelled CH4 fluxes averaged for all models were 1.07 of in situ CH4 flux (Fig. 7a). Some models overestimated the CH4 flux in the start of the growing season, and approximately 57 d after DOY of snowmelt variables not included in any of the models seemed to constrain in situ CH4 fluxes for all years and average modelled CH4 fluxes were on average 2.48 times the in situ CH4 fluxes (Fig. 7a). The models reproduce the pattern of the in situ fluxes well also in the end of the growing season, but they overestimated the fluxes considerably. In the further model evaluation, only modelled CH4 fluxes from days 1–57 after DOY of snowmelt will be used. The temporal variation in the input data is shown in Fig. 7b.

As can be seen in Table 5, there is on average not a large difference in model performance between the eight models. Model\(_{\text{sat}}\) 1–4 showed a slightly better correspondence (lower RMSE) to in situ CH4 flux in comparison to the respective Model\(_{\text{nosat}}\) 1–4 (Table 5). In addition, CH4 fluxes from Model\(_{\text{sat}}\) 1–4 were on average closer to the in situ values [average ratio from 1997, 2000, 2008 and 2009: 1.07 \( \pm \)0.14 (\( \pm \)1 SD)] than Model\(_{\text{nosat}}\) 1–4 (ratio: 1.18 \( \pm \)0.35) (Table 5). However, and most importantly, from the SDs (Model\(_{\text{sat}}\): 0.14 vs. Model\(_{\text{nosat}}\): 0.35) it can be seen that there were large differences in how well the models reproduced the inter-annual variations in the in situ CH4 fluxes. The smaller SDs for Model\(_{\text{sat}}\) indicate that they reproduced inter-annual variation better than Model\(_{\text{nosat}}\).

The linear function fitted between average modelled and

| Table 4. Parameters for the models relating temporal variation in CH4 fluxes and temporal variation in environmental variables |
|---------------------------------------------------------------|
| Plant communities     | Equation | Environmental variables | Parameter 1 | Parameter 2 | Parameter 3 | Parameter 4 | \( R^2 \) |
|-----------------------|----------|-------------------------|-------------|-------------|-------------|-------------|--------|
| Continuous fen        | Linear   | WtD                     | 11.11 \( \pm \)0.47 | 0.41 \( \pm \)0.07 | –            | –           | 0.81   |
| Hummocky fen          | Linear   | WtD                     | 4.10 \( \pm \)0.35 | 0.10 \( \pm \)0.05 | –            | –           | 0.34   |
| Continuous fen        | Eq. (3)  | \( T_{10} \)            | 4.50 \( \pm \)0.63 | –            | 0.13 \( \pm \)0.02 | –           | 0.79   |
| Hummocky fen          | Eq. (4)  | \( T_{10} \)            | 2.14 \( \pm \)0.45 | –            | 0.10 \( \pm \)0.04 | –           | 0.47   |
| Continuous fen        | Eq. (4)  | \( T_{10} \), AL        | 4.41 \( \pm \)0.59 | –            | 0.13 \( \pm \)0.02 | 0.17 \( \pm \)0.15 | 0.76   |
| Hummocky fen          | Eq. (4)  | \( T_{10} \), AL        | 1.97 \( \pm \)0.36 | –            | 0.11 \( \pm \)0.03 | 0.17 \( \pm \)0.15 | 0.54   |
| Continuous fen        | Eq. (5)  | WtD, \( T_{10} \)       | 7.38 \( \pm \)2.54 | 0.17 \( \pm \)0.15 | 0.06 \( \pm \)0.05 | –           | 0.85   |
| Hummocky fen          | Eq. (5)  | WtD, \( T_{10} \)       | 2.31 \( \pm \)0.98 | 0.01 \( \pm \)0.06 | 0.10 \( \pm \)0.05 | –           | 0.47   |
| Continuous fen        | Eq. (6)  | WtD, \( T_{10} \), AL   | 7.38 \( \pm \)2.54 | 0.17 \( \pm \)0.15 | 0.06 \( \pm \)0.05 | 0.17 \( \pm \)0.15 | 0.85   |
| Hummocky fen          | Eq. (6)  | WtD, \( T_{10} \), AL   | 2.31 \( \pm \)0.98 | 0.01 \( \pm \)0.06 | 0.10 \( \pm \)0.05 | 0.17 \( \pm \)0.15 | 0.47   |

Linear means a linear regression. Equations (3)–(6) are given in the text. \( a, b \) and \( c \) are fitted parameters, \( d \) was parameterised by Friborg et al. (2000), and \( R^2 \) is the coefficient of determination.
average measured values was also better correlated, the fitted curve was closer to a one-to-one relationship, and the intercept was closer to zero (Fig. 8a). This indicates that the models including NDWI as an explanatory variable were better in reproducing CH₄ flux variability.

Model sat 3 including temporal variations in WtD showed a weaker correspondence with measured data (larger RMSE) overall than the other models (Table 5). Model sat 4, which also included temporal variations in WtD, showed similar correspondence as Model sat 1. In addition, when temporal variations in WtD were not included the fitted linear functions were better correlated, the regression lines were closer to a one-to-one relationship, and the intercept was closer to zero (Fig. 8b). Including growing season variation in WtD in the models thus decreased the model performance.

Finally, the linear regression analysis showed that Model sat 1 and Model sat 2 were equally well correlated to in situ CH₄ fluxes. The fitted curves were equally close to a one-to-one relationship whereas the intercept was slightly closer to zero for Model sat 2 (Fig. 8c). However, the model with the best correspondence (lowest RMSE) to the in situ CH₄ fluxes was Model sat 2 (Table 5). Including AL in the models did, therefore, increase the model performance.

Fig. 4. The relationship between temporal variation in CH₄ fluxes to (a) averaged soil temperature at 10 cm depth and (b) averaged water table depth. Equation (3) is given in the text.

Fig. 5. Plot-averaged CH₄ fluxes against spatial variation in water table depth at the DOY of the satellite image 2007 (DOY 210).
The model evaluation indicated that all eight models performed well, but the model that performed the best was Model 2 (Table 5 and Fig. 8d).

3.3. Modelled CH4 fluxes 1997–2010

Modelled CH4 flux budgets accumulated for the first 57 d of the growing season ranged between 1.8 and 4.1 g CH4 m⁻² for Rylekærene over the period 1997–2010 (Fig. 9). Although there were large inter-annual variations in CH4 fluxes, no clear trend was observed (Fig. 10). The modelled CH4 fluxes over the study period was on average 2.0 mg CH4 m⁻² h⁻¹ with a model SE of 1.7 mg CH4 m⁻² h⁻¹ (Table 6), indicating a wide model uncertainty. A clear correlation was apparent between the CH4 fluxes and MODIS-based peak growing season NDWI ($R^2 = 0.80$, $n = 6$). There was also a correlation between the CH4 fluxes and $T_{10}$ at climate station C1 for days 1–57 of the growing season ($R^2 = 0.48$, $n = 7$). No significant changes in growing season $T_{10}$, or NDWI were apparent over the study period (Fig. 10).

4. Discussion

4.1. Environmental controls on growing season CH4 fluxes

In wetlands, CH4 is produced by methanogens under anaerobic conditions and oxidised by methanotrophs in the aerobic parts of the soil. The primary factor determining the distribution of anaerobic and aerobic conditions in wetlands is the combined influence of water and organic matter. Oxygen diffuses about $10^4$ times more slowly through water than through air, and organic matter supports a large biotic oxygen demand that consumes oxygen faster than it is replaced by diffusion (Megonigal et al., 2007). Consequently, it is not surprising that we found CH4 emissions from continuous and hummocky fen that both had shallow water tables, whereas they were undetectable in the dry plant communities (grassland, S. arctica snowbed and the heath communities) without a free-standing water table. Furthermore, the continuous fen had a water table close to the soil surface (Table 3 and Fig. 5), and consequently the largest CH4 fluxes. Continuous fen also had a high coverage of vascular plants. Vascular plants both act as conduits, facilitating the CH4 transport from the anaerobic parts of the soil to the atmosphere, bypassing the aerobic oxidation zone (Bubier and Moore, 1994) and affect the substrate availability for methanogens (Ström et al., 2012).

The darkening of the chamber did not have any direct effects on the in situ CH4 fluxes during our short chamber enclosure of 3 min, and this indicates that the CH4 fluxes were not directly affected by stomatal closure. An explanation could be a weak or slow response of stomatal closure to a sudden switch to dark conditions, as has been shown for other wetland plants (Torn and Chapin, 1993). An alternative explanation is that most of the CH4 fluxes were occurring through other pathways than through the stomata (Morrissey et al., 1993).

As expected, soil temperature influenced the temporal variability in CH4 fluxes strongly; the metabolic activity of both methanogens and methanotrophs is related exponentially to temperature (e.g. Dunfield et al., 1993).
response of CH$_4$ fluxes to soil temperature was equally well explained by a linear function for continuous fen. The different temperature dependencies for continuous and hummocky fen might be explained by spatially varying factors, such as substrate availability, hydrological conditions, metabolic activity of the methanotrophs or resistances along the transport pathways of CH$_4$ from the site of production to the atmosphere (Bubier and Moore, 1994). It could be that these spatially varying factors also explain the lack of spatial relationship between CH$_4$ flux and soil temperature. Another explanation could be the low spatial variation in soil temperature across the measurement area.

A strong correlation between both temporal and spatial variations in CH$_4$ fluxes and WtD was observed in 2007 (Fig. 4b and 5). In 2007, the measurements started late in the growing season, and as the WtD decreased over the growing season, so did the CH$_4$ fluxes. Water table depth affects the CH$_4$ fluxes, delimiting the zones for CH$_4$ production and oxidation. Still, the model evaluation indicated that including temporal variation in WtD decreased the performance of the CH$_4$ flux models (Fig. 8b) (for further discussion, see Section 4.3).

An additional factor influencing the zone for CH$_4$ production is the active layer thickness. The major part of the CH$_4$ production originates from the root zone where
there are readily available substrates for decomposition (Joabsson and Christensen, 2001). AL depth hereby exerts a stronger effect at the start of the growing season when AL is shallow, than later, when it is thicker. In 2007, the measurements started late in the growing season, and CH4 fluxes were already approaching their peak. An increase in AL did hereby not affect the CH4 fluxes and this can possibly explain the negative relationship between AL and CH4 flux seen in the 2007 data.

4.2. The relationship between soil hydrology and NDWI

There was a strong relationship between WtDcat and NDWI (Fig. 6), indicating a relationship between moisture content of the ground vegetation and the hydrological content in the soil. It should be noted that NDWI is a vegetation index sensitive to changes in plant liquid content at the leaf and canopy level (e.g. Gao, 1996). Normalised difference water index does not sense the absolute WtD, and it is hereby important not to interpret changes in the index as solely related to soil hydrology as it is strictly measuring ground surface properties. In a homogenous ground surface, such as the fen area in Rylekærene, the soil hydrology directly influences the growth patterns of the surface vegetation (Cronk and Fennessy, 2001). Wu et al. (2013) showed that plant biomass, vegetation cover and plant height were strongly correlated to wetland soil moisture. Previously, de Alwis et al. (2007) used NDWI to monitor temporal and spatial variations in surface water content and Goswami et al. (2011) showed that the normalised difference surface water index (NDSWI) was strongly correlated to surface hydrology for an Arctic wetland in Alaska. A similar water index to NDWI, the shortwave infrared water stress index (SIWSI), was shown to be strongly correlated to soil moisture in Senegal (Fensholt and Sandholt, 2003). In addition, in Fig. 2 it can be seen that the NDWI is not strictly following the plant phenology; high values were observed for the start of the growing season when high WtD (Fig. 7b) could be an additional factor affecting the index.

4.3. Validity of the modelled CH4 fluxes

While the models performed well on average for the first 57 d, i.e. ~69%, of the growing season (Table 5), they should be used with care. The temporal variation in modelled CH4 flux was strongly related to the soil temperature (Fig. 4a and Fig. 7). This relationship has been shown to be site-dependent, as previous studies have shown both strong relationships (Hargreaves et al., 2001; Rinne et al., 2007; Wille et al., 2008) and relationships that were weak or absent (Wickland et al., 2006; Sachs et al., 2008), as also observed for the continuous and hummocky fen in our study. The dependency of CH4 flux to soil temperature should therefore be investigated carefully before applying these models to other areas.

At the end of the growing season, the T10 was still high, resulting in relatively high CH4 fluxes according to the models (Fig. 7a and 7b). However, the field-measured CH4 fluxes were decreasing strongly at the end of the growing season. An explanation could be that the vegetation senescence results in lower substrate availability (Ström et al., 2012) and lower vascular plant-mediated CH4 transport. The vegetation senescence can be seen in the sharp decrease in NDWI after day 57 after DOY of snowmelt (Fig. 2).

Dynamics of the AL is an important factor for subsurface processes and including the effect of AL increased the accuracy of the modelled CH4 fluxes. The AL is constantly decreasing over the growing season (Fig. 7b), and this increases the zone for CH4 production. The increase follows the temporal variation in the CH4 flux for the start of the growing season. At the end of the growing season,

| Model | Equation | 1997 | 2000 | 2008 | 2009 | Mean all years | RMSE |
|-------|----------|------|------|------|------|---------------|------|
| 1nosat| (3)      | 0.88 | 1.59 | 0.83 | 1.32 | 1.16 ± 0.36   | 1.64 |
| 2nosat| (4)      | 0.83 | 1.48 | 0.78 | 1.17 | 1.07 ± 0.33   | 1.58 |
| 3nosat| (5)      | 1.63 | 0.85 | 1.43 | 1.31 ± 0.40 | 2.10 |
| 4nosat| (6)      | 1.52 | 0.80 | 1.25 | 1.19 ± 0.36 | 1.84 |
| Mean allnosat | 0.86 | 1.55 | 0.82 | 1.30 | 1.18 ± 0.36 | 1.67 |
| 1sat  | (9_3)    | 1.09 | 0.87 | 1.20 | 1.15 | 1.08 ± 0.15   | 1.61 |
| 2sat  | (9_4)    | 1.03 | 0.78 | 1.13 | 1.03 | 0.99 ± 0.15   | 1.50 |
| 3sat  | (9_5)    | 0.96 | 0.96 | 1.24 | 1.25 | 1.15 ± 0.16   | 1.94 |
| 4sat  | (9_6)    | 0.87 | 0.87 | 1.15 | 1.09 | 1.04 ± 0.15   | 1.62 |
| Mean allsat | 1.06 | 0.87 | 1.18 | 1.13 | 1.07 ± 0.14 | 1.56 |

Root mean square errors (RMSE) in mg CH4 m⁻² h⁻¹ for the different models are also included.
when AL is thick, CH$_4$ fluxes were instead restricted, and a change in AL presumably no longer had a major effect on the fluxes.

The models that included WtD as explanatory variable generally overestimated CH$_4$ flux in the start of the growing season (high values in model range in Fig. 7a). In addition, the regression analysis indicated that including temporal variation in WtD decreased the model performance (Fig. 8b). The WtD was at its peak at the start of the growing season, closely following snow melt, decreasing over the summer as runoff and evapotranspiration reduced soil water content (Fig. 7b). At the start of the growing season, CH$_4$ fluxes were uniformly low; most likely, low soil temperatures, low AL and undeveloped vegetation

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**Fig. 8.** Modelled CH$_4$ fluxes against in situ CH$_4$ fluxes. (a) Average of modelled CH$_4$ fluxes for all Model$_\text{no sat}$ and Model$_\text{sat}$ to show the difference between models with and without satellite-based NDWI; (b) Model$_\text{sat}$ 2 and Model$_\text{sat}$ 4 against in situ CH$_4$ fluxes to illustrate the difference between models including and excluding the temporal variation in WtD; (c) Model$_\text{sat}$ 1 and Model$_\text{sat}$ 2 against in situ CH$_4$ fluxes to illustrate the difference between models including or excluding the effect of AL; and (d) Modelled CH$_4$ fluxes modelled with Model$_\text{sat}$ 2 for the different years against in situ CH$_4$ fluxes.
limited CH$_4$ flux more than WtD. At the end of the growing season, WtD was again increasing, possibly due to temporal patterns in precipitation and evapotranspiration (Hasholt et al., 2008).

Water table depth still affects the CH$_4$ flux and the models performed better when remotely sensed NDWI was included, thereby accounting both for the inter-annual and spatial variation in ecosystem moisture content. Previous studies showing a positive relationship between CH$_4$ fluxes and WtD have also mainly showed spatial and long-term dependencies (Huttunen et al., 2003; Bubier et al., 2005; Pelletier et al., 2007; Rinne et al., 2007; Sachs et al., 2008; Wille et al., 2008). An additional explanation for why models incorporating NDWI performed better than the other models is that NDWI not only provides a metric of the ecosystem moisture content; it is also a proxy for vegetation density. This has two positive effects for the modelling of CH$_4$ flux. First, aerenchymatous species thrive in wet areas, and high NDWI values should hereby indicate a high density of vascular plants. Second, higher vegetation index values also indicate higher primary productivity (e.g. Tagesson et al., 2012a), representing enhanced substrate availability for methanogens (Joabsson and Christensen, 2001).

Previous studies have reported climate-related changes in vegetation composition in sub-Arctic and Arctic areas (Oechel et al., 1993; Malmer et al., 2005). The models derived in this study, however, implicitly assume constant plant community composition in Rylekærø over the period 1997–2010. Changes in plant communities, especially between plants with and without aerenchyma could bias the modelling of CH$_4$ emission (Oechel et al., 1993; Malmer et al., 2005). However, due to a lack of data on the vegetation dynamics of Rylekærø over the study period, no conclusions as to the possible influence of community composition on CH$_4$ variability can be drawn.

5. Conclusions

This study has addressed the spatial and temporal extrapolations of in situ measured data, a critical need within research on CH$_4$ fluxes from the Arctic. Our main aim is to investigate the applicability of combining in situ measurements with a remotely sensed vegetation index, NDWI, for spatial extrapolation of in situ-based CH$_4$ fluxes. Exponential and linear relationships between CH$_4$ fluxes and soil temperature, WtD and AL were used to estimate temporal variation in CH$_4$ fluxes. A spatial relationship between CH$_4$ flux and WtD was combined with a relationship between WtD and NDWI to spatially extrapolate the CH$_4$ fluxes. The evaluation of the models indicated that it was applicable to combine in situ measurements of CH$_4$ flux and NDWI for modelling growing season fluxes. On average, all models performed well, but the models including satellite-based NDWI reproduced the CH$_4$ flux variability better than the models not including NDWI. Even though the models performed well at this specific site, we would like to emphasise that further investigations are necessary before applying this model approach to other areas. Normalised difference water index, used here primarily as a proxy for WtD, is a vegetation index and attention should be paid to other site-specific factors, such as heterogeneous vegetation composition and soil type, that affect the index. All models overestimated the fluxes at the end of the growing season. A possible explanation could be that the vegetation senescence results in lower substrate availability and lower vascular plant-mediated CH$_4$ transport. Including these factors as predictors could be a way to improve the models in the future.

We found that the temporal variation in modelled CH$_4$ flux is strongly related to the soil temperature, WtD and AL thickness. However, we could also see that there are strong site differences in the dependency of CH$_4$ flux to soil temperature, and this relationship should therefore be investigated carefully before being applied to other areas. Incorporating a relationship between temporal variability in CH$_4$ flux and WtD decreased the model performance. Water table depth was high in the start and the end of the growing season when CH$_4$ flux was more constrained by other variables. However, spatial variability in CH$_4$ flux was strongly related to WtD and including NDWI (ecosystem moisture content) increased the model performance. This indicates that WtD mainly has spatial and long-term effects.

![Fig. 9. CH$_4$ fluxes modelled by Modelsat 2, averaged for the Rylekærø area, and accumulated over the first 57 d of the growing seasons 1997–2010.](image-url)
The model that performed best included soil temperature, AL and NDWI as explanatory variables. It was used for investigating trends in the CH$_4$ fluxes 1997–2010 at the studied high-Arctic wet tundra ecosystem. There was large inter-annual variation in modelled CH$_4$ fluxes; however, no distinct trend in CH$_4$ fluxes was seen over the study period. This may suggest that this area had fairly stable CH$_4$ fluxes over the study period, or that the main factors affecting the CH$_4$ fluxes have not changed significantly over this period. Indeed, no consistent trends were apparent in soil temperature at 10 cm depth and satellite-based NDWI.

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Table 6. Average ($\pm$ model SE) modelled CH$_4$ fluxes for the entire Rylekærøene area for the first 57 d of the growing season.

| Year | CH$_4$ fluxes (mg CH$_4$ m$^{-2}$ h$^{-1}$) |
|------|-------------------------------------------|
| 1997 | 1.5 ± 1.2                                 |
| 2000 | 2.3 ± 1.1                                 |
| 2002 | 2.9 ± 3.7                                 |
| 2007 | 1.6 ± 1.0                                 |
| 2008 | 3.0 ± 5.3                                 |
| 2009 | 1.4 ± 0.8                                 |
| 2010 | 1.5 ± 0.6                                 |

The model used for these estimates was the Model sat2. The variation in CH$_4$ fluxes due to heterogeneity in the modelled area is not included in the model SEs and it is strictly an estimate of the model uncertainty.

Fig. 10. (a) Accumulated modelled CH$_4$ fluxes day 1–57 of the growing season for Rylekærøene; (b) maximum MODIS-based NDWI for the NDWI peak period of the growing seasons in Rylekærøene 1997–2010; and (c) and average soil temperature at 10 cm soil depth at C1 day 1–57 of the growing season. The gap in the soil temperature 2005 was caused by broken soil temperature sensors.
7. Appendix

A.1. Abbreviations and symbols (Table A)

A.2. Calculation of model standard errors

As the model contained several modelled variables, the formula for error propagation was used to estimate the model SD ($\sigma^2_m$) (Leo, 1994).

$$\sigma^2_m = \left( \frac{df}{dx} \right)^2 \sigma^2_x + \left( \frac{df}{dy} \right)^2 \sigma^2_y + 2cov(xy) \times \left( \frac{df}{dx} \right) \times \left( \frac{df}{dy} \right)$$  (A.2.1)

where $\sigma^2_x$ and $\sigma^2_y$ is SD of model parameters. To simplify, we only give an equation for two variables here. However, in the SD calculations, we included errors from the five parameters in Model 2 [$a, c$ and $d$ in eq. (4); $k, l$ in eq. (9)], errors in the WtDcat modelled from NDWI, and finally for some of the years, errors from the parameters in the modelling of soil temperatures and AL. Finally, model SEs were calculated by dividing the SD with square root of the sample size. The variation in CH4 fluxes due to heterogeneity in the modelled area was not included in the model SE since average values of the modelled area were first calculated. It is strictly an estimate of the model uncertainty.

The average and SD of all model parameters was calculated in the fitting of the regressions. As the WtD was categorised after the linear regression between WtDcat and NDWI, the SDs of the model parameters could not be used in the calculation of the model SDs. The SD of the WtDcat was estimated by a Monte–Carlo sampling approach, for both continuous and hummocky fen.

| Abbreviation or symbol | Description |
|------------------------|-------------|
| $a$, $b$, $c$ and $d$ | Model parameters in Equations (3)–(6) |
| AL | Active layer thickness |
| ALmax | Peak active layer thickness measured during the growing season |
| C1 | Climate station (Fig. 1) |
| DOY | Day of year |
| $F_{CH4}$ | Methane flux |
| $F_{CH4,all}$ | Average chamber-measured methane fluxes from all plots |
| $F_{CH4,plot}$ | Plot-averaged chamber measured methane fluxes |
| $F_{CH4,frac}$ | Fraction of CH4 flux of an individual plot in relation to the average CH4 flux from all plots |
| $k$ | Intercept of exponential regression between $F_{CH4,frac}$ and WtDcat [eq. (8)] |
| $l$ | Growth constant of exponential regression between $F_{CH4,frac}$ and WtDcat [eq. (8)] |
| M1 | Monitoring site 1 |
| M2 | Monitoring site 2 |
| Modelnosat | Model data that do not include remote sensing data |
| Modelsat | Model data that do include remote sensing data |
| MODIS | Moderate resolution imaging spectroradiometer |
| NDWI | Normalized difference water index |
| NIR | Near-infrared wavelengths (780–900 nm) |
| RMSE | Root mean square errors |
| $\sigma^2_m$ | Model standard deviation |
| $\sigma^2_x$ | Standard deviation of a model parameter |
| $\sigma^2_y$ | Standard deviation of a model parameter |
| SWIR | Short-wave infrared wavelengths (1000–3000 nm) |
| SD | Standard deviation |
| SE | Standard error |
| $T_{10}$ | Soil temperature at 10 cm depth |
| T1997 | Tower site 1997 |
| $u$ | Intercept of linear regression between WtDcat and NDWI [eq. (2)] |
| $w$ | Slope of linear regression between WtDcat and NDWI [eq. (2)] |
| WtD | Water table depth |
| WtDcat | Categorized water table depth |
| $y$ | Year |
slope ($\mu$) and intercept ($\alpha$) between categorised WtD and NDWI was sampled randomly in a normal distribution around the average 2000 times. These 2000 sets of parameters were included into eq. (2), which were applied to each NDWI image in Table 1 for Rylekærene 1997–2010. Each of the 2000 estimates was classified into its respective WtD$_{sat}$. Average and SDs of the 2000 WtD$_{sat}$ estimates for Rylekærene were then calculated, for both continuous and hummocky fen.

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