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List of papers

I Torbern Tagesson, Mikhail Mastepanov, Mikkel P. Tamstorf, Lars Eklundh, Per Schubert, Anna Ekberg, Charlotte Sigsgaard, Torben R. Christensen and Lena Ström. High-resolution satellite data reveal an increase in peak growing season gross primary production in a high-Arctic wet tundra ecosystem 1992-2008. (Submitted).

II Torbern Tagesson, Meelis Mölder, Mikhail Mastepanov, Charlotte Sigsgaard, Mikkel P. Tamstorf, Magnus Lund, Julie M. Falk, Anders Lindroth, Torben R. Christensen and Lena Ström. Land-atmosphere exchange of methane from soil thawing to soil freezing in a high-Arctic wet tundra ecosystem. (Submitted).

III Torbern Tagesson, Mikhail Mastepanov, Meelis Mölder, Mikkel P. Tamstorf, Lars Eklundh, Benjamin Smith, Charlotte Sigsgaard, Magnus Lund, Anna Ekberg, Julie M. Falk, Thomas Friborg, Torben R. Christensen and Lena Ström. Inter-annual variability in growing season methane fluxes in a high-Arctic wet tundra ecosystem 1997-2010. (Submitted).

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V Mikhail Mastepanov, Charlotte Sigsgaard, Torbern Tagesson, Lena Ström, Mikkel P. Tamstorf and Torben R. Christensen. Revisiting factors controlling methane emissions from high-Arctic tundra. (Manuscript).

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IV I was involved in the field measurements, data handling, and writing of the manuscript.

V I was involved in the field measurements and writing of the manuscript.

Abstract

Arctic ecosystems play a key role in the terrestrial carbon (C) cycle, but spatially explicit data on the C exchange is scarce in these remote areas. The global warming is especially dominant in the Arctic, and these areas are vulnerable to climate change. It is therefore important to quantify and understand the processes affecting the C dynamics in these regions. In this thesis, the land-atmosphere exchange of C, with an emphasis on methane (CH_4), was measured in a high-Arctic wet tundra ecosystem (Rylekærene) in Zackenberg, north-eastern Greenland.

Rylekærene was a heterogeneous area concerning the source strength of CH_4 and concerning which environmental variables that best determine the CH_4 fluxes. For the central parts of Rylekærene, temporal variability in CH_4 fluxes was well correlated with soil temperature, gross primary production (GPP), active layer thickness and soil organic acids. The spatial variability in CH_4 fluxes was closely correlated to water table depth (WtD), species composition and soil organic acids. The CH_4 fluxes remained low during autumn and early winter of both 2008 and 2009. The central parts of Rylekærene acted as a C source during the warmer and wetter measurement season of 2008, whereas it was a C sink during the colder and drier measurement season of 2009.

At a site at the edge of Rylekærene, CH_4 emissions were lower than at the central parts of the fen, most likely because of lower WtD and different plant species composition. At this site, the variability in CH_4 flux was not explained by any of the above-mentioned factors. Increases in CH_4 fluxes coinciding with soil freezing after the growing seasons were observed here in 2007, 2009 and 2010.

Changes in peak growing season GPP 1992 to 2008 was investigated by combining satellite data with ground-based GPP measurements. The modeled results show a substantial increase in peak growing season GPP during this period. The GPP increase was accompanied by a strong increase in air temperature, possibly indicating that the increase in GPP was climate-driven.

Changes in CH_4 fluxes 1997-2010 was studied by combining satellite data with CH_4 flux measurements. During 1997-2010, there were no major changes in modelled CH_4 fluxes in Rylekærene, and during this period no trend in soil temperature at 10 cm depth and WtD were seen. However, as changes both in temperature and hydrology are expected as global warming continues, it can be assumed that such changes will have strong effects on the land-atmosphere exchange of C in wet tundra ecosystems in the future.

Keywords: carbon, methane, carbon dioxide, climate change, Arctic, NDVI, NDWI, micrometeorology, remote sensing, chamber, tundra

Sammanfattning

Under den senaste tiden har problematiken med klimatförändringarna debatterats livligt. För att kunna förutspå den framtida omfattningen av klimatförändringarna och vilka konsekvenser dessa kommer att ha är det ytterst relevant att känna till utbytet av växthusgaser mellan atmosfär och jordens alla ekosystem. Arktiska ekosystem är ytterst känsliga för den globala uppvärmningen. Därtill har temperaturökningen varit större i dessa områden och är förutspådd att bli ännu större i framtiden. Två växthusgaser av extra stor betydelse är koldioxid och metan.

De arktiska ekosystemen spelar dessutom en extra stor roll i kolutbytet mellan mark och atmosfär. Våtmarker på tundran är kalla, vattenfyllda och syrefattiga, vilket gör att nedbrytningen av dött organiskt material sker långsamt. Eftersom detta pågått sedan den senaste istiden, har stora mängder kol ansamlats i marken i dessa områden. Ca 16 % av jordens yta är täckt av permafrost, men 50% av jordens markbunda kol är lagrad i dessa områden. Dessutom gör dessa förhållandena att en stor del av slutprodukten av nedbrytningen av dött organiskt material är metan. Jag presenterar i denna avhandling studier av utbytet av koldioxid och metan mellan mark och atmosfär i en högarktisk våtmark belägen på Nordöstra Grönland.

Mina studier visade att våtmarken fungerade som en kolkälla under den varma och fuktiga mätperioden 2008. Medan den var en kolsänka under den kallare och torrare mätperioden 2009. Variationen i metanutbytet styrdes av marktempertur, växternas produktivitet, halt av substrat för metanproduktion (organiska syror), vattennivån i marken, samt växternas artsammansättning.

Jag har även undersökt växternas koldioxidupptag mellan 1992 och 2008 genom att kombinera fältmätningar av koldioxid med satellitbilder. Mina resultat visade på en kraftig ökning av koldioxidupptaget under denna tidsperiod. Under samma period skedde även en kraftig ökning av lufttemperaturen, vilket tyder på att det ökade koldioxidupptaget var klimatrelaterat. Jag studerade också metanutbytet mellan 1997 och 2010. Jag fann inga indikationer på förändringar i varken metanutsläpp eller i de faktorer som kraftigast styr metanutsläppen från våtmarken, d.v.s. marktemperatur på 10 cm djup och vattennivå.

Den globala uppvärmningen förutspås att fortgå i framtiden och globala klimatmodellerna förutspår framtida förändringar i såväl temperatur som nederbörd. Resultaten jag presenterar i denna avhandling visar på att dessa förutspådda framtida klimatförändringen kan ha en stark påverkan på kolcykeln i de högarktiskta ekosystemen.

Nyckelord: kol, metan, koldioxid, tundra, klimatförändringar, Arktis, NDVI, NDWI, mikrometeorologi, kammare, fjärranalys

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Introduction

Climate change

There is an increasing trend in the global mean air temperature. Since the end of the 19th century, the global average surface temperature has increased by 0.8°C (IPCC, 2007). The observed trend is most likely a result of an increase in the atmospheric concentration of greenhouse gases (IPCC, 2007). Greenhouse gases of particular importance are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Furthermore, the global mean air temperature is projected to increase an additional 1.8-4.0 ºC in the century to come (Meehl *et al.*, 2007). However, the temperature increase is not uniformly distributed across the globe. The increase both has been, and is projected to be more pronounced at high northern latitudes (ACIA, 2005, IPCC, 2007). The predictions for future increases in temperature are based on changes in albedo (as both depth and extent of ice and snow decreases), and on the fact that the current amount of water vapour is low, which results in a large effect of the expected increase in cloudiness trapping the reflected heat (Oechel & Vourlitis, 1997). Since 1900, the temperature has already increased ~2.2 ºC in the Arctic (McBean *et al.*, 2005), and the temperature increase is most pronounced over the land areas (Chapman & Walsh, 2003). The warming has additionally been accompanied by increased precipitation and a lengthening of the growing season (ACIA, 2005).

There are already substantial evidence for the effects of climate warming in the Arctic (Christensen *et al.*, 2004, Johansson *et al.*, 2006, Tarnocai, 2006). These are, for example, permafrost degradation, melting of snow, glaciers and sea ice, lengthening of the growing season, a shift in plant species composition, increased emissions of CH_4 and CO_2, and increased plant productivity (Christensen *et al.*, 2004, Johansson *et al.*, 2006, Malmer *et al.*, 2005, Oechel *et al.*, 1993, Serreze *et al.*, 2000, Svensson *et al.*, 1999, Tarnocai, 2006). The biosphere provides several possible feedback mechanisms between the biogeochemical cycles and the climate. Our current understanding of the coupling between the biosphere and climate system is limited and the projections of future climate are therefore highly uncertain. Considering the ongoing rise in temperature in the Arctic, and the vulnerability of the Arctic ecosystems to climate change, it is extremely important to quantify and understand the proc-

esses affecting the land-atmosphere exchange of greenhouse gases in these regions. One of the aims of this thesis is to contribute to these aspects.

Carbon in Arctic wet tundra ecosystems

Arctic wet tundra ecosystems play an important role in the global terrestrial carbon cycle. The waterlogged, anoxic and cool conditions in Arctic wetlands effectively reduce decomposition rates which have favoured the formation of peat during the Holocene (Smith *et al.*, 2004). Although, the northern permafrost region cover only about 16% of the global soil area, approximately 50% of the global soil organic carbon is today stored in these regions (McGuire *et al.*, 2009, Tarnocai *et al.*, 2009). This is more C than is stored in the entire global biosphere and the atmosphere added together (Chapin *et al.*, 2002, Tarnocai *et al.*, 2009).

Additionally, the waterlogged and anoxic conditions make wet tundra ecosystems ideal sites for CH_4 production. The atmospheric input of CH_4 from northern latitude wetlands account for about 25% of the total natural CH_4 sources globally (Schlesinger, 1997). Methane has a 25-fold global warming potential compared with CO_2 on a 100-year time basis (IPCC, 2007). Excluding the effect of water vapour, CO_2 have contributed to approximately 65% whereas CH_4 have contributed to about 22% of the greenhouse effect during the past 150 years (IPCC, 2007). The ongoing processes of thawing and warming of the Arctic might result in changes in the carbon regime in these regions. Small changes in the processes affecting the carbon accumulation, caused by changes in the temperature, water or permafrost regime may substantially alter the rate of carbon accumulation, or alter the balance between the CO_2 and the CH_4 gas emitted. It is critical to quantify the natural variability of carbon dynamics at these high northern latitudes to determine if these areas should be considered as future sources or sinks of carbon and radiative forcing.

Terrestrial carbon cycling

Carbon is assimilated by green vegetation through photosynthesis, where CO_2 is transferred from its oxidized form in the atmosphere into the biosphere, and its organic form, carbohydrates. In the process, energy is captured from the photosynthetic active radiation (PAR; 400-700 nm). The total photosynthesis at the ecosystem-scale is termed gross primary production. The energy assimilated through photosynthesis is used for maintenance, growth or reproduction by living organisms. Plants use about half of the gross primary production for their own growth and maintenance (Schlesinger, 1997), and this

CO_2 is released back to the atmosphere through autotrophic respiration. The remaining gross primary production (termed Net Primary Production) is stored in the ecosystem as biomass. This biomass is later consumed by herbivores, released to the atmosphere through disturbance, such as fire, or become part of the soil organic carbon pool. Finally, parts of the soil carbon pool is decomposed by soil biota, and released back to the atmosphere through heterotrophic soil respiration. The primary factors controlling gross primary produciton are leaf area index, growing season length, PAR, CO_2 concentration in the atmosphere, temperature, plant species composition, soil moisture and nutrient regimes (Chapin *et al.*, 2002). Controlling factors of heterotrophic soil respiration are soil temperature, soil moisture, physical soil properties, soil disturbance, substrate and litter quality and quantity, and microbial community composition (Chapin *et al.*, 2002).

In wet ecosystems, parts of the soil carbon pool is decomposed through anaerobic (no oxygen) metabolism and the most common end-product of this process is CH_4 (Conrad, 1996). Methane production is mainly a two way process with cooperation between methanogenic Archaea and anaerobic fermenting bacteria (Christensen, 2010). Complex organic matter is through a series of steps degraded by the fermenting bacterias into primary substrates for the methanogenic Archea, i.e. acetic acid, other carboxylic acids, alcohols, CO_2 and hydrogen (Christensen, 2010). Much of the easily decomposable carbon in soil is derived from roots, root residues and root exudates (Kuzyakov & Domanski., 2000).

Methane is however not only produced in wetlands; it is also oxidized by the microbial process of methanotrophy in the aerated upper part of the soil. The net CH_4 flux to the atmosphere is hereby the sum of methanogenesis in the anaerobic part of the soil, and the methanotrophy in the aerated part of the soil. Methane is mainly transported from the production sites in the anaerobic parts of the soil to the atmosphere through three main pathways; diffusion, ebullition and vascular plant mediated transport. The transport via diffusion exposes the CH_4 to methanotrophy in the aerated upper parts of the soil, while CH_4 released through ebullition pass the aerated part of the soil too fast to expose the CH_4 to the methanotrophy (Whalen, 2005). The final transport pathway is through vascular wetland plants that serve as gas conduit from the roots in the anaerobic zone to the atmosphere, and hereby bypassing the aerated oxidizing soil zone (Whalen, 2005).

The primary environmental controls of CH_4 production and fluxes are soil temperature, water table depth, transport pathway, pH and substrate quality and availability (Christensen, 2010, Whalen, 2005). There are still large uncertainties regarding the CH_4 source strength of wet tundra ecosystems, and its relationship to environmental variables. For example, Mastepanov *et al.* (2008) showed unexpectedly high CH_4 fluxes during the refreezing of the active layer.

Whalen & Reeburgh (1988), showed similar CH_4 fluxes for areas covered with mosses in Alaska where 40% of the annual fluxes were released during the freeze-in period. It is of very high relevance to quantify and understand the processes of the CH_4 fluxes in these ecosystems to understand the effects of a possible future climate change.

Aims and Objectives

In this thesis, I focus on the land-atmosphere exchange of carbon, with an emphasis on CH_4, in a high-Arctic wet tundra ecosystem. How well environmental variables determine the variability in carbon dynamics on different spatial and temporal scales were studied. I also investigated possible trends in environmental variables since the 1990's and what effects these could have on the land-atmosphere exchange of CH_4 and CO_2.

The main objectives of this thesis were to:

I. Quantify the current exchange of CH_4 and the CO_2 between a high-Arctic wet tundra ecosystem in north-eastern Greenland and the atmosphere, using both the closed chamber technique, and micrometeorological methods (Paper I-V).

II. Study how well environmental variables determine variability in CH_4 fluxes in a high-Arctic wet tundra ecosystem, at different temporal and spatial scales (Paper II-V).

III. Investigate changes in gross primary production 1992-2008, and CH_4 fluxes 1997-2010 for a high-Arctic wet tundra ecosystem in north-eastern Greenland (Paper I and III).

Materials and methods

Study site

The studies compiled in this thesis took place in Rylekærene (dunlin fens) in the Zackenberg Research Area (74°28´N 20°34´W), located in the Northeast Greenland National Park. Rylekærene is a patterned wet tundra ecosystem characterized by alternating sequences of elevated, dry heath areas and low wet fen areas. These sequences are mainly orientated in strings perpendicular to the hydrologic flow, which goes from northeast to southwest. The area is located in the high arctic zone (Walker *et al.*, 2005). The Zackenberg valley is located close to the coast and generally sheltered by high mountains, and the local temperature hereby is relatively mild. The long-term average temperature of the warmest month is 5.8 ºC, and the mean annual temperature is –9 ºC (Hansen *et al.*, 2008). The Zackenberg valley is underlain by continuous permafrost and the active layer thickness ranges between 0.5-1.0 m (GeoBasis, 2010). The dominant wind direction is N to NNW, except during the summer when the prevailing winds are S to SE. The dominant vegetation types identified in the Zackenberg valley are fen, grassland, *Cassiope tetragona* heath, *Dryas octopetala* heath, *Vaccinium uliginosum* heath and *Salix arctica* snowbed; which are distributed spatially based on topography, hydrology and soil type (Bay, 1998, Elberling *et al.*, 2008). Since 1995, extensive ecological, biogeographic, climatic, and hydrological research and monitoring has been carried out in the Zackenberg research area (Meltofte & Rasch, 2008).

Carbon flux measurements

The closed chamber technique

The chamber encloses a surface area for measuring fluxes at the plot-scale. This makes the method especially appropriate for studying spatial variation in C fluxes, in for example different plant communities or in different environmental conditions. We used two types of chamber systems, manual and automatic, both based on the closed chamber technique. For manual chamber measurements we used steady-state flow through closed chambers to estimate

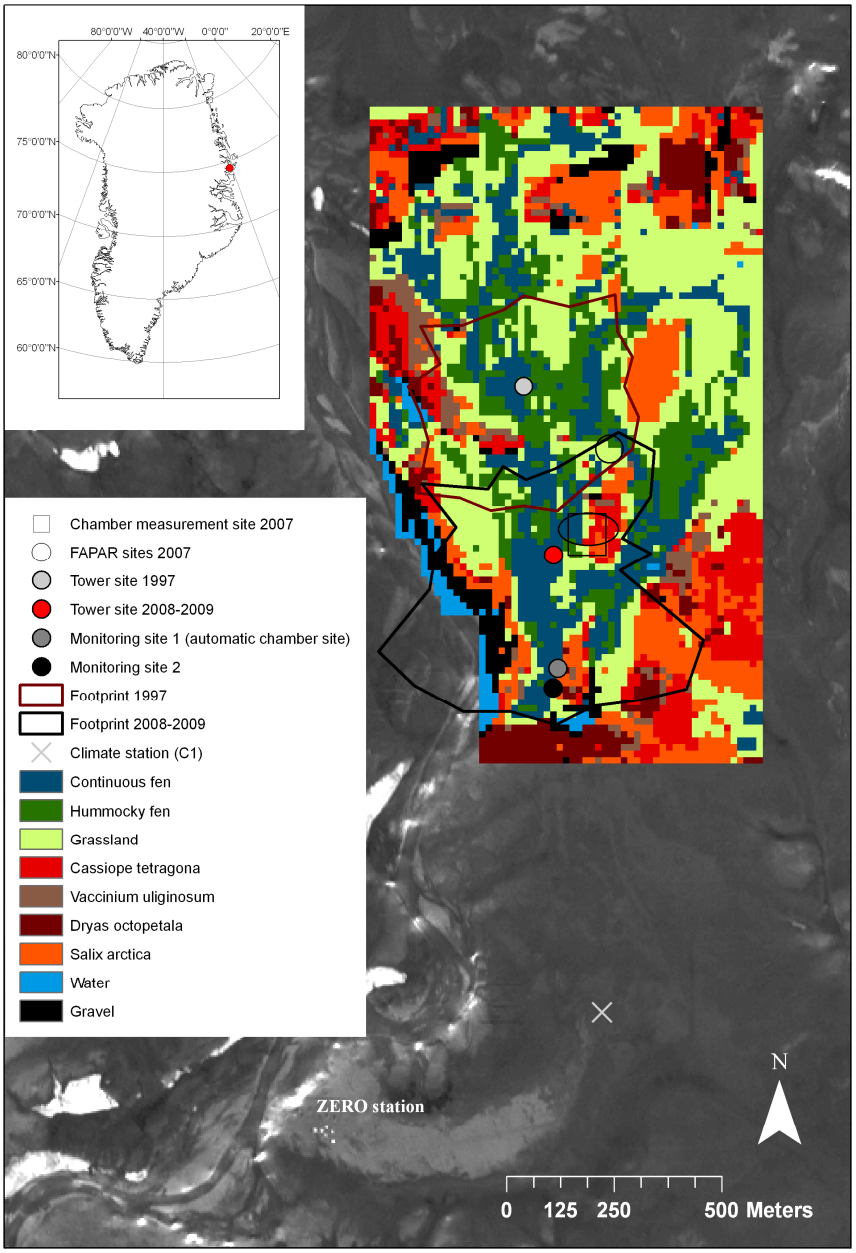

Figure 1. The Zackenberg valley and the investigation area surrounding the research station (ZERO). The field inventory map of the dominant plant communities in Rylekærene is superimposed over an IKONOS satellite image from July 2000. The red dot on the Greenland map is the location of Zackenberg. The footprint areas are the average 80% cumulative flux distances for the two towers (see text).

CO_2 and CH_4 fluxes in the centre of Rylekærene (Fig 1) (Livingston & Hutchinson, 1995) (Paper I, III, and IV). The CO_2 concentrations were measured with an infrared gas analyzer (EGM-4, PP-systems, Hitchin, Hertfordshire UK), and the CH_4 concentrations were measured with a laser off-axis integrated cavity output spectroscopy analyzer (DLT200; Fast Methane Analyzer, Los Gatos Research, USA). Net ecosystem exchange of CO_2 (NEE) was measured with a transparent chamber. Dark respiration was thereafter measured by covering the chamber with a lightproof hood. Gross primary production was calculated as the difference between NEE and respiration.

The automatic chamber system was used for measuring CH_4 fluxes and NEE at monitoring site 1 at the edge of the Rylekærene (Fig 1) (Paper V). The system consisted of six chambers with automatic lids that opened and closed once per hour for each chamber, respectively. The analytical box for the automatic system also consisted of a laser off-axis integrated cavity output spectroscopy analyzer (DLT-100; Fast Methane Analyzer, Los Gatos Research, USA) and an infrared gas analyzer (SBA-4, PP-systems, Hitchin, Hertfordshire UK) for measuring the chamber concentrations of CH_4 and CO_2, respectively.

Micrometeorological techniques

We used micrometeorological techniques for quantifying ecosystem-scale exchanges of CH_4 and CO_2. In comparison to the chamber measurements, it measures the exchanges nonintrusive. The most commonly applied technique is the eddy covariance (EC) technique. The EC technique depends on high frequency sampling of the vertical wind speed and a state variable. A tower was placed in the centre of Rylekærene (Tower site 2008-2009, Fig 1) so that fen areas were located in the main downwind directions. A small dry spot, located at one side of the tower, was equipped with a tent holding the measurement equipment. An open-path infrared gas analyzer (LI-7500: LI-COR Inc, Lincoln, USA) was installed at 3.3 m height in combination with a 3-axis sonic anemometer (USA-1; Metek, Gmbh, Elmshorn, Germany) for measuring atmospheric turbulence, and ecosystem-scale CO_2 exchange (Paper II).

Methane fluxes were measured by combining the gradient and the EC methods. The CH_4 concentration was measured at two levels (0.7 and 2.75 m) in the tower at 1 Hz rate. The system consisted of a laser off-axis integrated cavity output spectroscopy analyzer (DLT200; Fast Methane Analyzer, repeatability 1 ppb at 0.1 Hz, Los Gatos Research, USA). Similar to the molecular diffusion, vertical fluxes of CH_4 can be determined using the gradient method by the vertical gradient of CH_4, and an atmospheric diffusion coefficient obtained by the sonic anemometer measurements (Foken, 2008).

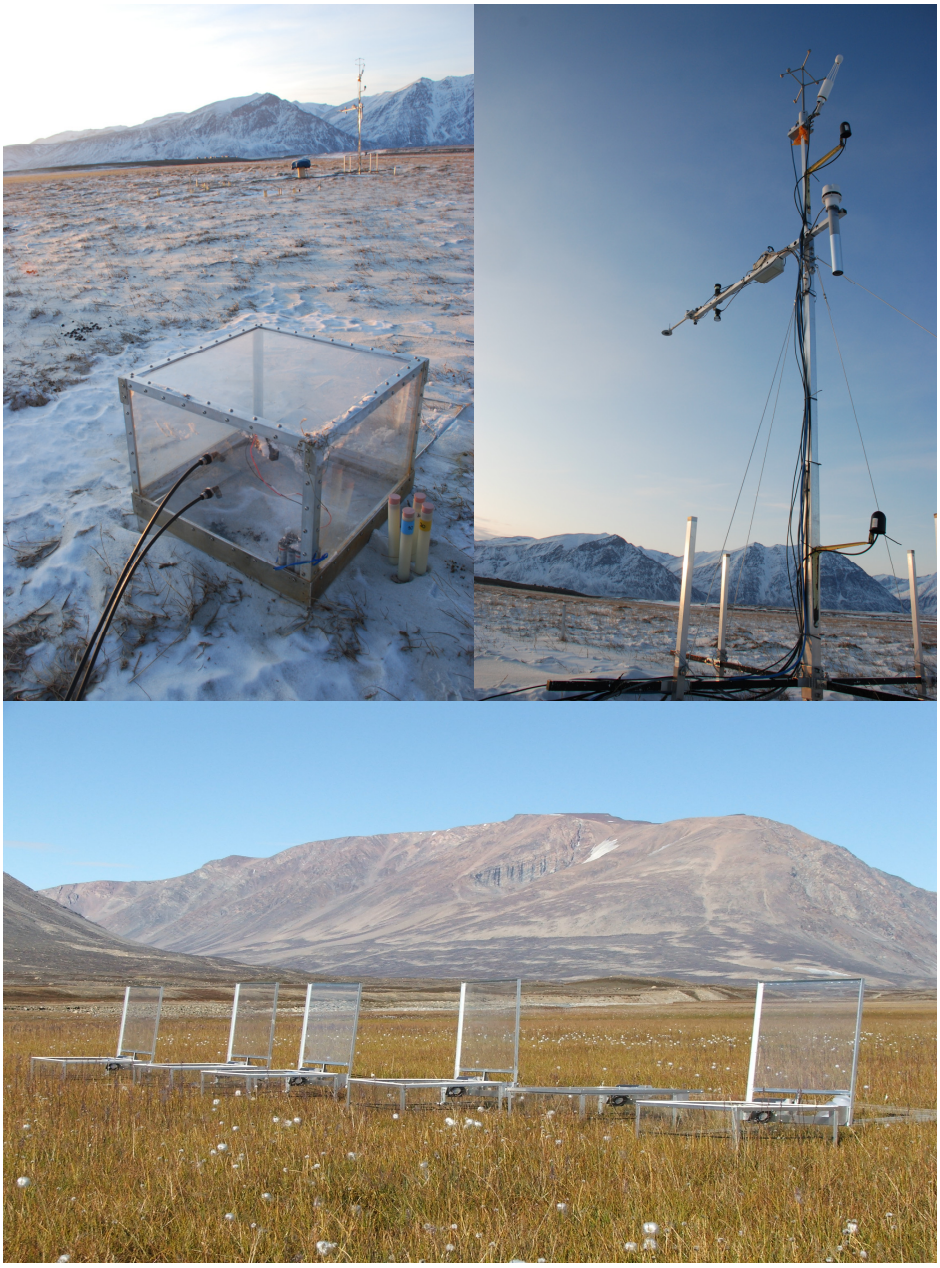

Figure 2. Carbon flux measurement techniques. A chamber used for manual plot-scale measurements, the tower used for micrometeorological ecosystem-scale measurements, and the automatic chambers used for automatic plot-scale measurements of the C fluxes.

Environmental variables

In addition to the CO_2 and CH_4 flux measurements, a range of environmental variables were measured, i.e., soil and air temperature, PAR, active layer thickness, water table depth and soil gas pressure.

Soil temperature at 0.05, 0.10 and 0.15 m depth (Tinytag Plus, Gemini Data Loggers, UK) were (1) measured at the monitoring site 1, (2) at 0.02 and 0.05 m at the tower site 2008-2009 using Copper-Constantan thermocouples, (3) at 10 cm depth near each manual chamber measurement plot simultaneously to the flux measurement and (4) at 10 different depths between 0 and 1.30 m at the Climate station (C1) 1995-2010 (ClimateBasis, 2010). See Fig 1 for specific locations.

Air temperature, precipitation and snow depth were additionally measured at the Climate station (C1) 1995-2010 (ClimateBasis, 2010).

Incoming and reflected PAR was measured with JYP 1000 sensors (SDEC, France) at the FAPAR (fraction of absorbed photosynthetic active radiation) sites in 2007. It was also measured inside the manual chamber, simultaneously to the flux measurement 2007.

Soil gas pressure profiles at 10, 20, 30 and 40 cm depth (relative to the atmospheric pressure) were measured in 2008 (24PCEFA6G, Honeywell S&C, Morristown, USA) at four plots in the surrounding of the tower.

Active layer thickness and water table depth were measured manually at the (1) chamber measurements site 2007, (2) the monitoring site 1 2007-2010 and (3) in the vicinity of the tower 2008-2009.

Vegetation survey

In order to get a detailed description of the plant communities within the Rylekærene area, the dominant plant communities were recorded every 15 m^2 (positions according to a Magellan SporTrakPRO GPS, Thales Navigation, Carquefou Cedex, France) within a 1.4 km^2 rectangle covering Rylekærene and its close surroundings (Fig 1) (Paper I). The sampling points were divided into the dominant plant communities: continuous and hummocky fen, grassland, *Cassiope tetragona* heath, *Dryas octopetala* heath, *Vaccinium uliginosum* heath and *Salix arctica* snowbed. Non-vegetated areas were separated into gravel and water. Additionally, species coverage was estimated for the surface area covered in the manual chamber measurements in the 2007 field season.

Substrate analysis

To estimate the readily available substrates for methanogenesis pore water was sampled (directly after some of the manual chamber measurements) in 2007

and analysed for low weight molecular organic compounds (LMWOC), i.e., organic acids, amino acids and carbohydrates using liquid chromatography-ionspray tandem mass spectrometry. The instrumental set-up consisted of a Dionex ICS-2500 liquid chromatography system directly coupled to an Applied Biosystems 2000 Q-Trap triple quadrupole mass spectrometer (MS); see Paper IV for additional set-up and analytical details.

Remote sensing

A large portion of the red part of the solar radiation spectra is absorbed by chlorophyll during photosynthesis while radiation in the near infrared part of the spectra is reflected due to structures within the leaves (Lillesand *et al.*, 2008). This is commonly used within remote sensing to calculate vegetation indexes, such as the normalised difference vegetation index (NDVI):

$$\mathrm{NDVI} = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red}) \quad (1)$$

where ρ_{NIR} is reflectance in the near infrared (NIR) band and ρ_{red} is the reflectance in the red band.

A number of studies have used short wave infrared (SWIR) wavelengths to investigate ecosystem moisture status (Boles *et al.*, 2004, de Alwis *et al.*, 2007, Delbart *et al.*, 2005, Gao, 1996, Xiao *et al.*, 2004). Reflectance in these wavelength regions are known as water absorption bands, as they are highly sensitive to water content in the soil and vegetation surface (Lillesand *et al.*, 2008). Gao (1996) proposed the normalized difference water index (NDWI), equivalent to the NDVI but with the SWIR band instead of the red band, to estimate vegetation liquid water. In this thesis, NDVI and NDWI were calculated from reflectance data from the Landsat thematic mapper (TM) and enhanced thematic mapper (ETM+), the Satellite Pour l'Observation de la Terre (SPOT), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (Aster), and the IKONOS satellites (Paper I and III).

Empirical modelling

A widely applied approach within remote sensing is to estimate plant productivity by a light use efficiency model (Monteith, 1972, Monteith, 1977). The light use efficiency model allows gross primary production to be estimated from the photosynthetically active radiation absorbed by the green vegetation ($APAR_{green}$). $APAR_{green}$ can in turn be computed from incoming PAR and the fraction of photosynthetically active radiation absorbed by the green vegetation ($FAPAR_{green}$):

$$GPP = \varepsilon \times PAR \times FAPAR_{green} \quad (2)$$

where, ε is the light use efficiency of the vegetation. In this thesis, ε and $FAPAR_{green}$ were measured in the field during the peak of the growing season 2007. A linear regression was fitted between $FAPAR_{green}$ and satellite-based NDVI. The field measured ε and the fitted $FAPAR_{green}$ versus NDVI regression was incorporated into equation 2. Incoming PAR and satellite-based NDVI were used as model input data. The model was evaluated against field-measured gross primary production. NDVI based on a set of satellite images from the peak of the growing seasons 1992-2008 were used to study changes in peak growing season gross primary production during this period (Paper I).

Four different regression models were fitted against temporal variation in field measured CH_4 fluxes. Model 1 included soil temperature at 10 cm depth, Model 2 soil temperature at 10 cm depth and active layer thickness, Model 3 water table depth and soil temperature at 10 cm depth and Model 4 soil temperature at 10 cm depth, water table depth and active layer thickness. Measured environmental variables for Rylekærene were used as input data in the models. We combined the modelled CH_4 fluxes with remotely sensed NDWI to spatially extrapolate the modelled CH_4 fluxes over Rylekærene (Paper III). The models were evaluated against field-measured CH_4 fluxes. Finally, Model 1 was used in combination with remotely sensed NDWI to estimate inter-annual variability in CH_4 fluxes 1997-2010.

Results and discussion

Environmental conditions

The average annual air temperature 1996-2009 was -9.0 ºC in the Zackenberg valley (ClimateBasis, 2010). Over this period, there has been a strong increase in air temperature. The annual mean air temperature has on average increased by 0.11 ºC y^{-1}, 1996-2009. The increase has been especially dominant in the winter months (December, January, and February: 0.37 ºC y^{-1}) and the summer months (June, July and August: 0.18 ºC y^{-1}). The soil temperature between 0 and 130 cm depth has, however, so far not been affected by the increase in air temperature for any parts of the year except during summer. An explanation could be the insulating snow layer covering the soil during the winter months. There was an increasing trend in soil temperatures between 0 and 130 cm depth for the summer months 1996-2009 though (0.07 ºC y^{-1}) (ClimateBasis, 2010). However, there was a large variation between the different soil depths. There was an increasing trend in soil temperature for the most upper soil layers (0 and 2.5 cm depth), and at 20, 40 and at 130 cm depth. There was no increase in soil temperature at 5 and 10 cm depth and at between 60 and 100 cm depth. The sensors measuring soil temperature at C1 were replaced after the growing season in 2006. It could be that there was a disturbance at the measurement site when the new sensors were installed. It could also be different microstructures in different soil layers with different heat holding capacity (Romanovsky & Osterkamp, 2000). Another explanation could be that the energy was transmitted into permafrost thawing. In support of this theory, average peak active layer thickness (70 cm 1997-2010) increased 1997-2010 by 1.6 cm per year at the circumpolar active layer monitoring (CALM) site in the vicinity of C1 in the Zackenberg valley (GeoBasis, 2010). Soil heat may also be lost through emission to the atmosphere as sensible and latent heat; evapotranspiration was modelled for 1998-2004, and the modelled results indicate an increasing trend over this period, especially after 2000 (Hasholt *et al.*, 2008). In contrast to what has been seen for other parts of the Arctic (ACIA, 2005) the warming was not accompanied by any change in precipitation or length of the growing season 1995-2010. The average total precipitation was 214 mm 1996-2009. As for precipitation in general, no significant trend in snow depth for the period 1998-2010 was seen in the Zacken-

berg valley. The growing season was defined to start at the day when the snow melted and end the first of two consecutive days with a soil temperature of 0ºC at 2.5 cm depth (Tamstorf *et al.*, 2007). In this thesis, the day the snow depth exceeds 10 cm was used as proxy for day of snowmelt. The growing season length was on average 83 days 1995-2010. Snow depth was started to be measured 1998 at C1 (Fig 1). If snow depth data from C1 was used for the period 1998-2010, there was an increasing trend in growing season length during this period (1.4 day y^{-1}). However, if modelled snow-cover data from Buus-Hinkler *et al.* (2006) was used for the period 1995-1997, there was no trend in growing season length 1995-2010.

In Paper III, we show a strong correlation between water table depth and satellite-based NDWI. No trend in peak season NDWI was seen 1997-2010 for Rylekærene indicating no large-scale changes in water table depth during this period in the study area.

Current exchange of CH_4 and CO_2

(I) Spring

The C fluxes were low during spring 2009 (Table 1). On three occasions (21, 23 and 28 May 2009) higher CH_4 emissions, up to 1.91 mg CH_4 m^{-2} h^{-1}, were observed though. However, since these occasions lasted only for short periods they did not have any visible effect on the annual budget (Fig 3, Paper II). The observed high emissions were simultaneous to the start of the snow melt, possibly indicating a release of CH_4 from the snow cover, as it settled during the initial stage of the snow thawing. No extra CH_4 bursts occurred as the ice covering the fen was melting, as has been indicated by previous studies (Hargreaves *et al.*, 2001, Tokida *et al.*, 2007, Wille *et al.*, 2008).

(II) Growing season

There were large temporal and spatial variations in the measured carbon fluxes (Table 1). The level of the CH_4 fluxes from Rylekærene were large in comparison to other northern wetlands, but still in the same range (Corradi *et al.*, 2005, Friborg *et al.*, 2000, Hargreaves *et al.*, 2001, Rinne *et al.*, 2007, van Huissteden *et al.*, 2005, Whalen & Reeburgh, 1988). The measured CO_2 fluxes were also in the same range as has been found in other studies in Arctic ecosystems, using both EC and closed chamber techniques (Arndal *et al.*, 2009, Corradi *et al.*, 2005, La Puma *et al.*, 2007, Lafleur & Humphreys, 2008, Nobrega & Grogan, 2008, Soegaard & Nordstroem, 1999, Wille *et al.*, 2008).

It should be pointed out that we observed a large discrepancy between the plot-scale automatic chamber-based CH_4 fluxes and the ecosystem-scale

Table 1. The measured carbon fluxes for the different years and the different sites (see Fig 1 for specific locations). GPP is the gross primary production and NEE is the net ecosystem exchange of CO_2. AC is the automatic chamber measurements. MC1 is the manual chamber measurements in 2007. CF is plots in continuous fen, HF hummocky fen, CFE continuous fen dominated by *Eriophorum Scheuchzeri*, CFCD continuous fen dominated by *Carex stans* and/or *Dupontia psilosantha*, G grassland, SS *Salix arctica* snowbed, VU *Vaccinium uliginosum* heath, CT *Cassiope tetragona* heath and DO *Dryas octopetala* heath. Tower is the footprint of the tower site 2008-2009. A negative value defines an uptake by the measured ground area.

Year	Period	Site	CH_4 flux (mg CH_4 m^{-2} h^{-1})	GPP (mg CO_2 m^{-2} h^{-1})	Respiration (mg CO_2 m^{-2} h^{-1})	NEE (mg CO_2 m^{-2} h^{-1})	Paper
2006	3/7-26/8	AC	2.36	-	-	-93	V
2007	24/6-6/9	AC	2.61	-	-	-131	V
2007	25/6-2/8	MC1_CFE	11.40	-1156	612	-546	IV
2007	25/6-2/8	MC1_CFCD	5.44	-860	452	-409	IV
2007	30/6-4/8	MC1_CF	9.14	-654	369	-290	I, III
2007	30/6-4/8	MC1_HF	3.59	-581	350	-252	I, III
2007	30/6-4/8	MC1_G	0.12	-475	332	-144	I, III
2007	30/6-4/8	MC1_SS	-0.04	-239	208	-37	I, III
2007	30/6-4/8	MC1_VU	-0.02	-218	187	-31	I, III
2007	30/6-4/8	MC1_CT	-0.03	-215	188	-23	I, III
2007	30/6-4/8	MC1_DO	-0.03	-188	140	-38	I, III
2007	7/9-24/10	AC	4.26	-	-	405	V
2008	23/6-25/8	AC	0.85	-	-	-317	V
2008	24/6-16/9	Tower	4.89	-391	288	-103	II
2008	17/9-24/10	Tower	0.78	-	-	181	II
2008	9/10-16/10	AC	0.11	-	-	-	V
2009	16/5-31/5	Tower	0.19	-	-	56	II
2009	1/6-6/9	Tower	3.32	-471	327	-144	II
2009	6/6-6/9	AC	1.21	-	-	-59	V
2009	7/9-24/10	AC	0.92	-	-	151	V
2009	7/9-28/10	Tower	1.26	-	-	91	II
2010	23/6-18/9	AC	0.87	-	-	-59	V
2010	19/9-2/11	AC	0.55	-	-	337	V

micrometeorological measurements with much lower fluxes at the automatic chamber site. We argue that this may simply reflect areas of differences in hydrology and species composition. The automatic chamber site is located at the edge of the fen (Fig 1) and it is generally drier than the central parts of the fen (where the manual chamber measurements and the micrometeorological measurements were conducted). There is no apparent difference in total vas-

cular plant coverage between the sites. There is, however, a slightly different vascular plant composition at the automatic chamber site, with a higher coverage of the grass *Arctagrostis latifolia*. *Arctagrostis latifolia* is common in drier parts of the Zackenberg valley (such as grasslands and on hummocks in hummocky fen). The high cover of this grass at the automatic chamber site indicate drier conditions which would result in lower CH_4 production and possibly also different transport and storage conditions in this area. In addition, the explanation to the low CH_4 fluxes at the automatic chamber site in 2008, when the fluxes were the highest in the central parts of the fen, could be due to refilling of the storage after the autumn burst in 2007 (Paper V).

We argue that there might be large changes in hydrology in the area surrounding the automatic chamber site during the last 10 years. Offering support to the theory of ongoing change is a study conducted 10 years ago in a site positioned only meters away from the present day automatic chamber site (Christensen *et al.*, 2003, Joabsson & Christensen, 2001). In 1999 and 2000, the mean flux from this site was 6.5±0.6 and 8.3±0.5 mg CH_4 m^{-2} h^{-1}, respectively, indicating a substantial change in the magnitude of the flux over these 10 years.

(III) Autumn and early winter

The autumn and early winter was defined as the end of growing season until 31 October. The micrometeorological measurements did not show any autumn CH_4 emission pulse during the onset of soil freezing, as has been suggested by land-atmosphere CH_4 flux measurements conducted at the automatic chamber site, and atmospheric concentration measurements at high northern latitudes (Dlugokencky *et al.*, 1994, Khalil & Rasmussen, 1983, Mastepanov *et al.*, 2008). At the automatic chamber site, increased CH_4 fluxes coinciding with soil freezing were measured in 2007, 2009 and 2010 (Paper V). In 2007, after the gradual decrease of CH_4 fluxes during the end of growing season and through the zero curtains, the fluxes started to increase again and peaked with extremely high values up to 112.5 mg CH_4 m^{-2} h^{-1}. The peak of this late-season emission was observed around 7 October 2007. The registered amount of CH_4 emitted during this period in 2007 (Table 1) was about 90% of the estimated growing season CH_4 fluxes. In 2008, the few existing measurements at monitoring site 1 showed very low fluxes with no evidence of a late-season peak. During 2009, the first signs of a late-season emission peak were registered on 20 September; however, the following fluxes were not as high as in 2007. Only three days of very high fluxes (up to 99 mg CH_4 m^{-2} h^{-1}) were registered in one of the chambers at 20-22 October 2009.

There are few studies addressing the issue of wintertime CH_4 fluxes in permafrost areas (Mastepanov *et al.*, 2008, Whalen & Reeburgh, 1988, Wille *et al.*,

2008). Whalen and Reeburgh (1988) showed that 40% of the annual fluxes were winter fluxes from moss covered surfaces in Alaska, whereas no increases were seen for other vegetation covers. Wille *et al.* (2008) did not see any increase in the CH_4 fluxes as the soil started to freeze in the Lena delta, north-eastern Siberia. Both Mastepanov *et al.* (2008) and Whalen and Reeburgh (1988) explained the increase in CH_4 fluxes as the soil started to freeze with physical processes. When the soil started to freeze down towards the permafrost bottom, soil gas pressure increased. Accumulated CH_4 cannot diffuse downwards due to the impermeable permafrost bottom, and it is therefore pressed up through voids in the frozen soil matrix (Whalen & Reeburgh, 1988), or through the aerenchyma of senescent vascular plants (Hargreaves *et al.*, 2001, Mastepanov, 2010). On 23 September 2008, there was indeed a strong increase in soil gas pressure as the soil started to freeze (Paper II). Despite the increase in soil gas pressure, there was no increase in the CH_4 fluxes visible in the micrometeorological measurements.

A reasonable explanation for the lack of autumn CH_4 fluxes in the micrometeorological measurements is that other environmental conditions need to be fulfilled for the increase in CH_4 flux to occur. It might be that it is also necessary with an accumulation of CH_4 produced during the growing season. Whalen and Reeburgh (1988) only observed increased CH_4 fluxes during soil freezing in moss covered areas. Measurements at plots with vascular plants did not show any increase in CH_4 fluxes. Vascular plants facilitate the transport of CH_4 to the atmosphere and the presence of vascular plants hereby depletes the concentration of CH_4 in trapped gas bubbles in the saturated rhizosphere and the dissolved CH_4 pool in the pore water (Shannon *et al.*, 1996). As described above, there is no apparent difference in total vascular plant coverage between the automatic chamber site and the central parts of Rylekærene. However, the different vascular plant composition could possibly indicate lower plant mediated CH_4 transport during the growing season. This could result in a CH_4 accumulation at the automatic chamber site, which then can be released through voids in the frozen moss matrix.

An interesting feature in the micrometeorological measurements was the bursts of CH_4 in the end of October 2008 (Paper II). It might be that some accumulated CH_4 existed in cracks in the frozen soil and the moss and vegetation layer. The high wind speed increased the turbulence, which then resulted in turbulence-induced large-scale ebullition, possibly triggered by changes in air pressure and ventilation of these cavities (Aurela *et al.*, 2002, Black *et al.*, 2000, Massman *et al.*, 1997). No similar phenomena were seen in 2009, but a 0.30 m deep snow layer insulated the soil from the atmosphere in 2009. Similar phenomena could not be observed in the chamber measurements as the ground surface was decoupled from the atmospheric turbulence inside the chamber.

Drivers of variation in CH_4 flux

Temporal variation

There were strong seasonal variations in the CH_4 fluxes in Rylekærene (Table 1). During the spring period, we found no correlations between variability in CH_4 fluxes in the micrometeorological measurements and any of the measured environmental variables. The low correlations could be explained by that the CH_4 fluxes were very low during this period, and there were not much variation.

It has been shown that the start of the growing season greenhouse gas exchange at high-Arctic areas is strongly controlled by timing of the snow melt (Groendahl *et al.*, 2007). Consequently, we chose to set the day of snowmelt to the start of the growing season. The results from both the micrometeorological measurements, and the automatic chamber measurements (Paper II and V) confirmed the findings by Groendahl *et al.* (2007) and showed a clear relationship between timing of the snow melt and start of the growing season greenhouse gas exchange in Rylekærene.

Soil temperature was a variable that described the temporal variation in growing season CH_4 fluxes in the central parts of the fen well. The soil temperature at 5 cm soil depth had the strongest correlation with growing season CH_4 fluxes measured with the micrometeorological method (Paper II), possibly indicating that most CH_4 was produced at this depth (Bubier & Moore, 1994). The metabolic activity of both methanogens and methanotrophs is directly affected by the soil temperature and the relationship has an exponential character (e.g. Bubier & Moore, 1994, Dunfield *et al.*, 1993). The relationship seems to be site dependent, as previous studies have shown both strong (Hargreaves *et al.*, 2001, Rinne *et al.*, 2007, Wille *et al.*, 2008) as well as weak or no correlation (Sachs *et al.*, 2008, Wickland *et al.*, 2006). When the relationship between the net CH_4 fluxes and soil temperature deviates from the exponential character, there must be additional factors than CH_4 production that exerts a stronger control on the net CH_4 emissions. Possible explanations could be substrate availability, metabolic activity of the methanotrophs and resistance in the CH_4 transport to the atmosphere. The relationship between CH_4 fluxes and soil temperature had an exponential character for the micrometeorological measurements (Paper II). The manual chamber measurements in 2007 had something between a linear and an exponential relationship (Paper III). The automatic chamber measurements were not correlated to soil temperature (Paper V).

The water table depth regulates the sizes of the zones for CH_4 production and oxidation (Bubier & Moore, 1994). The strength of the correlations between CH_4 fluxes and water table depths varied between sites and years. In the

manual chamber measurements 2007, there was a close correlation, for both continuous and hummocky fen (Paper III). However, the model evaluation indicated that including seasonal variation in water table depth decreased the model performance (Paper III). In the micrometeorological measurements, a weak positive linear relationship between daily average CH_4 fluxes and water table depth existed for the growing season 2009, whereas a negative linear relationship to water table depth was seen in 2008. At the automatic chamber site, no correlations were seen (Paper V).

The water table depth is usually at its peak right after the snowmelt, in the beginning of the growing season. Over the summer, the water runs off and is evapotranspired. In the beginning of the growing seasons, when the water table was close to the soil surface, low CH_4 fluxes were measured. In 2007, the measurements started late in the growing season, and CH_4 fluxes were already heading towards the peak. Then as the water table depth decreased during the growing season, so did the CH_4 fluxes. For the other sites and the other years, low CH_4 fluxes were measured in the beginning of the growing seasons, when the water table depths were high, which hereby gave low correlations. In Paper III, the model evaluation indicated that models including inter-annual variation in water table depth performed better than models not including long-term variation in water table depth. Previous studies showing a positive relationship between water table depth and CH_4 fluxes have also mainly showed spatial, and inter-annual dependencies (Bubier *et al.*, 2005, Huttunen *et al.*, 2003, Pelletier *et al.*, 2007, Rinne *et al.*, 2007, Sachs *et al.*, 2008, Wille *et al.*, 2008).

The active layer thickness is an additional factor controlling the zone of CH_4 production (Friborg *et al.*, 2000). The major part of the CH_4 fluxes originates from the root zone where fresh substrates are available for decomposition (Chanton *et al.*, 1995, Ström & Christensen, 2007), which means that a deepening of the active layer below the root zone does not necessarily lead to higher CH_4 production.

Additional important variables regulating the CH_4 fluxes are the quantity and quality of the substrates to be decomposed (Joabsson & Christensen, 2001, Whiting & Chanton, 1993). Fresh organic matter from root exudates and recently produced litter are important sources of methanogenic substrate (Chanton *et al.*, 1995, Ström & Christensen, 2007). There was indeed a close relationship between seasonal variation in CH_4 fluxes and organic acids, where of >85% was acetic acid (Paper IV). The availability of these substrates are closely linked to gross primary production (Joabsson & Christensen, 2001), and there was also an observed strong relationship between the CH_4 fluxes and gross primary production for the micrometeorological measurements (Paper II). This has also been shown in previous studies (Friborg *et al.*, 2000, Joabsson & Christensen, 2001, Whiting & Chanton, 1993).

During the autumns and early winters of 2008 and of 2009 no clear relationships between environmental variables and the micrometeorological measurements of CH_4 fluxes were found (Paper II). In 2007 and 2010, however, there was a close relationship between autumn emissions of CH_4 and the gradual freezing of the soil layer at the automatic chamber site (Paper V).

Spatial variation

Methane is produced by methanogens under anaerobic conditions, and we therefore found CH_4 emissions from continuous and hummocky fen, whereas the dry plant communities (grassland, *Salix arctica* snowbed, and the heath communities) did not have any detectable CH_4 fluxes (Table 1). The continuous fen had the highest CH_4 fluxes and correspondingly the water table closest to the soil surface (Paper III). Another explanation could be a higher coverage of vascular plants (Bubier & Moore, 1994). Species composition could also affect the CH_4 fluxes (Ström & Christensen, 2007, Ström *et al.*, 2005). In Paper IV, it was shown that *Eriophorum scheuchzeri*, common in the continuous fen, had a very strong effect on the CH_4 emissions in Rylekærene. The mean seasonal CH_4 flux was twice as high in *Eriophorum scheuchzeri* dominated plots than plots dominated by *Carex stans* and/or *Dupontia psilosantha*, most likely due to a 1.7 times higher concentration of organic acids in these plots (>85% acetic acid). It was additionally shown that there were strong correlations between spatial variation in CH_4 fluxes and gross primary production, NEE and plant biomass.

There were exponential relationships between spatial variation in CH_4 fluxes and water table depth, for both continuous and hummocky fen (Paper III). As previously mentioned, the water table depth defines the zones for CH_4 production and oxidation. In Paper III, models including satellite images performed better than models without the satellite images, since they incorporated the inter-annual and spatial variation in water table depth. Previous studies have also shown spatial relationships between water table depth and CH_4 fluxes (Huttunen *et al.*, 2003, Rinne *et al.*, 2007, Sachs *et al.*, 2008, Wille *et al.*, 2008).

Trends in peak growing season gross primary production 1992-2008

The model evaluation indicated that the parameterized light use efficiency model was applicable for the Rylekærene area. Subsequently, it was applied to a set of satellite-based NDVI ranging from 1992 to 2008 to estimate changes in peak-growing season gross primary production in Rylekærene. During this period, there was a substantial increase in peak growing season gross primary

production for this high-Arctic wet tundra ecosystem (Paper I). It is expected that gross primary production for high-latitude ecosystems would increase as the climate is warming (Oechel *et al.*, 2000, Shaver *et al.*, 2000), and correspondingly the average annual air temperature in the Zackenberg area also increased between 1992 and 2008. Photosynthesis, as most chemical reactions, is temperature-limited at low temperatures (Chapin, 1987, Kummerow *et al.*, 1980, Tieszen, 1973). An increase in temperature also increases soil nutrient availability due to increased weathering, nitrogen fixation (Sorensen *et al.*, 2006) and decomposition of soil organic matter (Robinson *et al.*, 1997). Consequently, an increase in soil nutrients could explain the increased gross primary production 1992-2008. Additionally, warming increases reproductive efforts for many plant species (Walker *et al.*, 2006), which could result in an increased plant cover.

The globally averaged CO_2 concentration at the sea surface has increased on average 1.8 ppm per year since 1992 (Tans, 2009). Elevated atmospheric CO_2 concentrations are frequently used to explain increased gross primary production (e.g. Loustau *et al.*, 2001). Higher concentrations of atmospheric CO_2 both increase photosynthesis, and decrease photorespiration (Loustau *et al.*, 2001). Additionally, it reduces stomatal conductance, which decreases the water loss due to transpiration (Chapin *et al.*, 2002). However, it is highly debated if it has any long term effects, due to other anatomical, genetic, demographic, community, and ecosystem-level controls on gross primary production (Oechel *et al.*, 1997).

The temperature increased continuously during the 1992 to 2008 study period. However, the modelled gross primary production levelled off after 2002 (Fig 5, Paper I). The species dominating the Zackenberg area have their normal distribution range further north in Greenland, and are less common further south (Bay, 1992). Consequently, these species are adapted to lower temperatures, and an increase therefore only has positive effects on photosynthesis to a certain limit. A larger temperature increase may push the species outside their normal temperature range and not affect plant photosynthesis as positively. This could explain the decrease in the gross primary production trend after 2002.

There was a clear drop in modelled gross primary production in 2005 (Paper I). This year had the highest average annual temperature and the earliest snowmelt 1992-2008 (7 June). Additionally, it was the third year in a row with low precipitation (Hansen *et al.*, 2008). The decrease in modelled gross primary production 2005 might be explained by drought. In addition, the winter and spring temperatures were unusually high and this led to several thaw events and a low snow-cover (ClimateBasis, 2010, Ellebjerg *et al.*, 2008). It could be that the low snow cover resulted in vegetation damage from wind and ice, which could lead to decreased plant productivity during the subse-

quent growing season. Previously, it has been shown that winter warming episodes can lead to widespread vegetation damage and reduced plant productivity (Bokhorst *et al.*, 2009). Additionally, the modelled gross primary production increased after 2005 (Fig 5, Paper I), possibly due to a gradual recovery of the vegetation. The predicted increase in winter temperatures for the future (Stendel *et al.*, 2008) may therefore have major consequences for the productivity of these Arctic ecosystems.

Trends in growing season CH_4 fluxes 1997-2010

There was no trend in modelled growing season CH_4 fluxes 1997-2010 for the parts of Rylekærene observed to be continuous and hummocky fen 2007 (Fig 8, Paper III). Neither was any significant change observed in growing season soil temperature at 10 cm depth, or NDWI 1997-2010 for Rylekærene (see above) (Paper III). Methane fluxes were only modelled for the first 57 days after snowmelt, leaving open the possibility of greater variation in the end of the growing season. However, generally, the CH_4 fluxes are more even between years in the end of the growing season (Paper V), and the small inter-annual variation in growing season lengths would not have any large effect on the trend in CH_4 fluxes 1997-2010.

Previous studies have concluded that the observed increased CH_4 fluxes were mainly caused by thawing permafrost and related changes in vegetation composition (Bubier *et al.*, 1995, Christensen *et al.*, 2004, Johansson *et al.*, 2006). The boundary between permafrost features (palsas and peat plateaus) and fen areas have the highest CH_4 fluxes (Bubier *et al.*, 1995). In Zackenberg, there is continuous permafrost, and these areas are not as vulnerable to thawing permafrost as regions with sporadic or discontinuous permafrost (Johansson *et al.*, 2006).

General circulation models predict warmer and wetter climate in north-eastern Greenland (Stendel *et al.*, 2008). It might be expected that further air temperature increases in the area will eventually lead to an increase in soil temperature, and if combined with wetter conditions to an associated, positive effecting on the CH_4 fluxes.

Conclusions

The focus of this thesis was on the land-atmosphere exchange of carbon in a high-Arctic wet tundra ecosystem (Rylekærene) in Zackenberg, north-eastern Greenland, with a special emphasis on CH_4 emissions. Rylekærene was a heterogeneous area in the source strength of CH_4 flux largely due to different water regimes and plant communities. In the wet community types, the CH_4 fluxes were high, but still within the same range as other studies in comparable ecosystems.

During spring 2009, small increases in the CH_4 fluxes were observed in the central parts of Rylekærene. These were simultaneous with the start of snow melting, possibly indicating a release of stored CH_4 as the snow settled during snow thawing. However, these fluxes were observed during short periods and did not have any significant effect on the annual budgets.

In 2007, manual chamber measurements of CH_4 fluxes were done over the peak growing season in different plant communities in the central parts of the fen. High growing season emissions of CH_4 were seen for continuous and hummocky fen, 9.14 mg CH_4 m^{-2} h^{-1}, and 3.59 mg CH_4 m^{-2} h^{-1}, respectively. The dry plant communities (grassland, *Salix arctica* snowbed, *Cassiope tetragona* heath, *Dryas octopetala* heath, and *Vaccinium uliginosum* heath) did not have any detectable CH_4 fluxes.

In the central parts of the fen, CH_4 fluxes measured with micrometeorological methods were larger in 2008 (4.89 mg CH_4 m^{-2} h^{-1}) than in 2009 (3.32 mg CH_4 m^{-2} h^{-1}), possibly due to the fact that 2008 was a wetter and warmer year. The soil temperature, gross primary production, soil organic acid concentrations and active layer thickness were environmental factors with high correlation to the growing season CH_4 fluxes at the central parts of Rylekærene.

At a site at the edge of Rylekærene, CH_4 fluxes were lower than at the central parts of the fen. At this site we found large inter-annual variation in CH_4 fluxes between 2006 and 2010. The growing season 2007 had the highest average CH_4 fluxes (2.57 mg CH_4 m^{-2} h^{-1}) and 2008 was the year with the lowest average CH_4 fluxes (0.82 mg CH_4 m^{-2} h^{-1}). No measured environmental variables explained the CH_4 flux variability at this site. Most likely, there were some other factors exerting a stronger control on the CH_4 fluxes, such as substrate availability, metabolic activity of the methanotrophs or resistance in the CH_4 transport to the atmosphere.

The large spatial variation in growing season CH_4 fluxes shown in the area were mainly explained by differences in species composition and water table depth. A high coverage of vascular plants facilitates the CH_4 transport from the anaerobic parts of the soil to the atmosphere. It was also shown that *Eriophorum scheuchzeri* (common in the continuous fen) increased the CH_4 fluxes due to a high production of acetic acid in its root vicinity, giving easily available substrate for the methanogens.

Methane fluxes were low during the autumn and early winter 2008 and 2009 in the central parts of the fen. At the site at the edge of Rylekærene large bursts of CH_4 coinciding with the gradual freezing of the active layer after the growing season were observed in 2007, 2009 and 2010. In 2007, the soil-freezing season bursts were even comparable in size to the growing season emissions. There was a strong increase in soil gas pressure after the 23 September when the soil started to freeze in 2008. The lack of an increase in CH_4 emissions in the micrometeorological measurements indicates that it is not enough with an increase in soil gas pressure for an autumn burst to occur. A reasonable explanation is that it was also necessary with accumulated CH_4 produced during the growing season that can be emitted in the period of the soil freezing. At the site of the automatic chambers, there is a slightly different plant species composition and slightly drier conditions. It could be that this affected the growing season CH_4 emissions so that more CH_4 is stored, and then later emitted during soil freezing.

By applying a light use efficiency-model to a satellite data set of NDVI ranging from 1992 to 2008, a substantial increase in peak-growing season gross primary production in Rylekærene 1992-2008 was shown. The gross primary production increase was accompanied by a strong increase in air temperature. This could indicate that the increase in gross primary production was climate-driven.

The trend in growing season CH_4 fluxes in Rylekærene 1997-2010 was investigated by combining field-measured CH_4 flux measurements with a satellite-based water index (NDWI). During 1997-2010, there were no major changes in soil temperature at 10 cm depth and water table depth at the site, and the modelled CH_4 fluxes during this period correspondingly show no significant trends. However, the future predictions for the north-eastern Greenland are increased temperatures and increased precipitation. This wet tundra ecosystem may thus play a more significant role for the climate in the future.

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