EDDY COVARIANCE MEASUREMENTS OF METHANE FLUX IN A SUBARCTIC FEN WITH EMPHASIS ON SPRING-MELT PERIOD

BY

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ABSTRACT

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Reliable determinations of ecosystem scale fluxes of net carbon (C) and greenhouse gases for northern peatland ecosystems are of great value to determine the impact of soil warming and altered precipitation on emissions. Additionally, few studies have been performed which measure the C fluxes, particularly methane flux (F_{CH4}), during the spring melt and fall freeze up periods, therefore making it difficult to provide adequate annual C estimates from northern peatland ecosystems. This study aimed to determine ecosystem scale F_{CH4} from a eutrophic Subarctic fen at Churchill, Manitoba (58°45'N 94°4'W), to understand (a) seasonal trends over two consecutive growing seasons,(b) if over-winter stored CH_4 was released as a pulse during the spring-melt period, and (c) soil temperature - F_{CH4} relations for modelling F_{CH4} over the spring-melt period. An ecosystem scale methane (CH_4) and carbon dioxide (CO_2) flux measurement system using the eddy covariance (EC) technique was used from late-June to mid-October of 2008 and early-June to late-September of 2009, with focus on the spring-melt period of late-May to mid-July of 2009. The EC flux measurement system consisted of a closed-path RMT-200 Fast Methane Analyzer (Los Gatos Research Inc.) along with a LI-7500 open-path CO_2/H_2O gas analyzer (LI-COR Biosci.) and a CSAT3 3-dimensional sonic anemometer (Campbell Sci.). The system was powered by a combination of wind, solar, and gas electric generation. The EC flux measurement system provided seasonal F_{CH4} values of 0 – 90 nmol CH_4 m^{-2} s^{-1}, similar to previous studies in Subarctic and Arctic peatlands which incorporated the EC technique. A melt period CH_4 emission burst was

not observed, rather a gradual increase in emission over the spring period. Modelled F_{CH4} using a temperature-response curve relationship with soil temperature at 5 cm depth over the spring-melt period (May 30 – July 19, 2009) showed the fen to be a net source of CH_4, of 1.4 mmol m^{-2} CO_2 equivalent.

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“Anyone can appreciate the Rockies, but one needs to appreciate subtlety in order to see the true beauty of the tundra and the prairies” – Dr. W.F. Rannie

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1. INTRODUCTION

1.1 The greenhouse effect and global warming

Greenhouse gases (GHGs) in the earth's atmosphere absorb infrared radiation and radiate energy back towards the earth's surface. Warming of the earth by this process is a natural phenomenon called the "greenhouse effect". However, human activities that increase the concentration of GHGs in the atmosphere, and thus increase surface warming and slow the release of heat to space create what is called the "enhanced greenhouse effect" [*ACIA*, 2004]. The main anthropogenically-enhanced GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons, with CO_2 and CH_4 being the most significant contributors [*Forster et al.*, 2007]. Atmospheric concentrations of CO_2 [CO_2] have increased from the pre-industrial level of 280 ppm to 379 ppm by 2005, primarily due to the combustion of fossil fuels. Methane concentrations [CH_4] have increased from 715 ppb during pre-industrial times to 1774 ppb by 2005 [*Forster et al.*, 2007]. Although atmospheric [CH_4] is much lower than [CO_2], CH_4 has a global warming potential (GWP) 25 times greater than that of CO_2 over a 100 year time scale, where the GWP for CO_2 is 1 over 100 years [*Forster et al.*, 2007].

The global response to the enhanced greenhouse effect is estimated to be a mean annual temperature increase of 0.1 – 1.5°C by the year 2100, based on predictions of the Coupled Climate-Carbon Cycle Model Intercomparison Project (C^4MIP) [*Friedlingstein et al.*, 2006; *McGuire et al.*, 2009]. The circumpolar north will be most greatly affected, and mean annual temperatures for the Arctic are expected to increase by 3 – 5°C by the year 2100 [*ACIA*, 2004]. Increased temperature in the Arctic is one of many environmental changes; precipitation is expected to increase, snow and ice cover will decrease, and winters are expected to be shorter and warmer [*ACIA*, 2004; *Forster et al.*, 2007].

1.2 Methane as a contributor to climate change

Methane is emitted to the atmosphere from anthropogenic sources such as fugitive methane losses for natural gas exploitation and use, landfills, and agricultural practices, particularly rice paddies, enteric fermentation of livestock, and manure [*Forster et al.*, 2007]. Peatlands and wetlands are a natural source of CH_4 to the atmosphere due to their high water tables and anaerobic conditions [*Limpens et al.*, 2008].

Methanogenesis, the production of CH_4, is performed by a group of obligate anaerobic bacteria called methanogens belonging to the kingdom Euryarchaeota in the domain Archaea [*Lai*, 2009]. Methanogenesis occurs under anaerobic conditions with reduction potential (Eh) < -200 mV [*Yu and Patrick*, 2004]. Acetotrophic methanogens use acetate (CH_3COO^-), while hydrogenotrophic methanogens reduce CO_2 while using hydrogen (H_2) to produce CH_4 as the end product of heterotrophic respiration [*Yu and Patrick*, 2004; *Lai*, 2009]. Methanotrophy, the consumption of CH_4, is performed by methanotrophs belonging to the kingdom Euryarchaeota in the domain Eubacteria [*Lai*, 2009]. Methanotrophy occurs under aerobic conditions with Eh > -200 mV by obligate methanotrophic bacteria [*Yu and Patrick*, 2004] which oxidize CH_4 through the pathway of methanol (CH_3OH), formaldehyde (CH_2O), formate ($CHOO^-$), and finally CO_2 [*Lai*, 2009].

In peatlands, methane is transported to the atmosphere through three different pathways; diffusion, ebullition, and plant-mediated transport [*Lai*, 2009]. High [CH_4]

within the anaerobic zone of peat results in a [CH_4] gradient to the atmosphere which drives molecular diffusion [*Lai*, 2009]. This upward movement of CH_4 provides a substrate for methanotrophs in the aerobic layer near the peat surface, which limits the [CH_4] introduced to the atmosphere [*Lai*, 2009]. Due to the low solubility of CH_4 in water of the anaerobic zones, CH_4 emission through the process of molecular diffusion is minimal [*Reddy and DeLaune*, 2008; *Lai*, 2009].

Ebullition is the release of CH_4 in gas bubbles to the atmosphere from peat. When CH_4 production within the anaerobic zone of peat occurs at a high rate, bubbles are released from the soil due to the higher partial pressure of dissolved gases than the hydrostatic pressure of the surrounding peat [*Lai*, 2009]. The bubbles expand within the pores of the peat until the pores are over-pressurized and the gas bubbles are ejected [*Strack et al.*, 2006; *Lai*, 2009]. Ebullition typically results in a release of very high [CH_4] to the atmosphere in a sudden burst, prohibiting consumption by methanotrophs in the aerobic soil layer [*Lai*, 2009].

Plant-mediated transport of CH_4 from the anaerobic soil layer to the atmosphere occurs through aerenchyma tissues in hydrophytic plants such as sedges which act as conduits for gas transport to and from the plant roots [*Strack et al.*, 2006]. Aerenchyma allows oxygen (O_2) to be transported from the atmosphere to the plant roots which are within the anaerobic zone of the soil. Methane produced in the anaerobic zone can move through the plant roots directly to the atmosphere via aerenchyma, bypassing the CH_4 consumption zone [*Strack et al.*, 2006; *Reddy and DeLaune*, 2008].

During peak productivity in hydrophytes such as *Carex aquatilis*, CH_4 produced in the soil is transported within the plant through aerenchyma [*Morrissey et al.*, 1993;

Reddy and DeLaune, 2008], and released to the atmosphere through stomatal conductance [*Morrissey et al.*, 1993; *Schimel*, 1995], with plants closing stomates when under stress, inhibiting the transfer of CO_2 and CH_4 [*Syed et al.*, 2006; *Lafleur and Humphreys*, 2007]. Later in the season when plants begin to senesce, energy is expended on root biomass, rather than the above-ground portions of the plant [*Heide et al.*, 1985; *Griffis and Rouse*, 2001]. The onset of senescence and browning of the leaf tips of *C. aquatilis* in the late summer period reduces the cuticle on the leaf surface and allows for cuticular conductance, a more resistant pathway than stomatal conductance [*Morrissey et al.*, 1993]. Once fully senesced, the dominant CH_4 transport mechanism is cuticular conductance from hydrophytes [*Morrissey et al.*, 1993], with additional contributions from diffusion through soil and water, and ebullition [*Reddy and DeLaune*, 2008]. As a result CH_4 emissions in the fall become much smaller. Transport mechanisms are similar in the spring, with young emergent leaves of *C. aquatilis* transporting CH_4 from aerenchyma to the atmosphere via cuticular conductance, in addition to diffusion and ebullition [*Morrissey et al.*, 1993].

1.3 Northern peatlands and climate change

Peatlands are organic wetlands that have more than 40 cm peat accumulation [*NWWG*, 1997]. In Canada, 67% of all peatlands are bogs, and 32% are fens [*NWWG*, 1997]. Bogs are at or above the water table and are acidic (pH near 4.5). Acidity results because the dominant vegetation is Sphagnum mosses and because bogs are ombrogenous [*NWWG*, 1997]. Fens are minerogenous, with water which flows through and above the surface. They are dominated by graminoids and shrubs [*NWWG*, 1997], and are slightly acidic to neutral in pH [Tarnocai, 2006].

Peatlands cover a significant portion of the circumpolar north. Approximately 350 x 10^6 ha of land within Russia, Canada, Fennoscandia, and the United States is occupied by peatlands which store a third of the world's soil organic C [*Gorham*, 1991]. Of all Canadian land area, peatlands cover approximately 13% [*Environment Canada*, 1986]. In permafrost regions of Canada, 112 Pg C is stored in peatlands [*Tarnocai et al.*, 2007]. It has been suggested that 85% of Subarctic peatlands and 49% of boreal peatlands in Canada will be severely or extremely severely affected by climate change [*Tarnocai*, 2006] based on the sensitivity model by *Kettles and Tarnocai* [1999]. This is of great importance because Subarctic and boreal regions contain 97% of the soil organic C pool of Canadian Peatlands [*Tarnocai*, 2006].

With increased warming in northern regions, it is suggested that peatlands could experience a lowering of the water table allowing them to become drier and be more susceptible to fires and aerobic decomposition, thus releasing more CO_2 to the atmosphere [*Tarnocai*, 2006]. If precipitation were to increase as well, as has been suggested [*ACIA*, 2004], unfrozen peatlands that become wetter could allow for peat accumulation and C sequestration. However, peatlands underlain with permafrost that become wetter could allow for greater anaerobic decomposition and thus release of more CH_4 to the atmosphere [*Tarnocai*, 2006].

1.4 The Hudson Bay Lowlands and climate change

The Hudson Bay Lowlands (HBL) are located along the southwest and southern shores of Hudson Bay through the provinces of Manitoba, Ontario and Quebec [*Scott*, 1995]. Approximately 75% of the HBL are wetlands and peatlands [*Tarnocai*, 1984; *Scott*, 1995]. The Subarctic region of the HBL is located in Manitoba near Churchill and is underlain by continuous permafrost [*Scott*, 1995]. These peatlands are very young and are greatly influenced by the parent material. Due to isostatic rebound since the last glaciations, 1500 – 3000 years ago, most peatlands within 20 km of the shore of Hudson Bay are fens and protobogs, having not yet developed into true bog forms [*Scott*, 1995]. The Subarctic region of the HBL is the most sensitive to climate change, and increasing temperature and precipitation could result in a wetter environment that releases additional stored C in the form of CH_4 to the atmosphere from fens and protobogs.

1.5 Previous studies of CH_4 and CO_2 fluxes in northern peatlands

Since the early 1990's, many studies have focussed on C fluxes in northern peatland systems of the Netherlands, Norway, Sweden, Finland, Siberia, Greenland, Alaska and Canada. These studies have monitored C fluxes using chamber and micrometeorological techniques such as eddy covariance (EC).

In the Netherlands, *Veenendaal et al.* [2007] studied CO_2 exchange in a fen meadow site from October 2004 – September 2005. Their study involved an open-path EC system over drained peat soil which was not underlain by permafrost [*Veenendaal et al.*, 2007]. *Hendriks et al.* [2007] studied fluxes of CO_2, CH_4 (F_{CH4}), and N_2O (F_{N2O}) at the Horstermeer Research Site in a permafrost-free peat meadow from January 1, 2004 –

December 31, 2006. An open-path EC system was used to study CO_2 fluxes, while closed dark chambers were used to study F_{CH4} and F_{N2O} [*Hendriks et al.*, 2007]. In June of 2006, a closed-path EC system was introduced to measure continuous ecosystem scale F_{CH4}, and compared to results from closed dark chamber measurements [*Hendriks et al.*, 2008].

Svensson et al. [1999] studied CO_2 fluxes and F_{CH4} for the Subarctic Stordalen mire, in the northern portion of Norway. The mire had a hummock and hollow topography, with hummocks being underlain by permafrost [*Svensson et al.*, 1999]. Both CO_2 fluxes and F_{CH4} were studied using static chambers from June 17 – September 9, 2004 and April 2 – October 14, 2005 [*Svensson et al.*, 1999].

Several C flux studies have been undertaken in Swedish peatlands. *Mikkela et al.* [1995] studied CH_4 emissions from a boreal ombrotrophic mire near Umea, Sweden. Static vented chambers were used on July 17 – 18 and September 10 – 11, 1991, and August 30 – 31, 1992 to determine diurnal variations in CH_4 emissions [*Mikkela et al.*, 1995]. *Nilsson et al.* [2008] measured CO_2 fluxes and F_{CH4} from the Degero Stormyr mire complex in Northern Sweden. A closed-path EC system was implemented for CO_2 fluxes, while opaque static chambers were used to measure F_{CH4} over the 2004 and 2005 growing seasons [*Nilsson et al.*, 2008]. *Petrescu et al.* [2008] modelled F_{CH4} with the PEATLAND-VU model and compared the results to measured values obtained with automated chambers at the Stordalen Mire.

The study of C fluxes in northern peatlands is at the forefront of research in Finland. *Komulainen et al.* [1999] studied CO_2 fluxes from a drained minerotrophic fen and ombrogenous bog from the southern boreal region of Finland. Clear, ventilated and thermostated plastic chambers and aluminum shades were used to capture net CO_2

exchange and respiration [*Komulainen et al.*, 1999]. *Hargreaves et al.* [2001] used the EC technique with tunable diode laser spectroscopy to determine F_{CH4} on three separate occasions: August 1995, May – June 1997, and September – October 1998. The study site was an aapa mire near Kaamanen, Finnish Lapland, with the presence of ice lenses in hummocks [*Hargreaves et al.*, 2001]. *Heikkinen et al.* [2002] reported F_{CH4} and CO_2 fluxes at the Kaamanen aapa mire for the 1995 growing season as well. Static chambers were used to measure net ecosystem exchange of CO_2 and F_{CH4} from June – September, and an EC system using tunable diode laser spectroscopy was used to determine F_{CH4} for late August [*Heikkinen et al.*, 2002]. *Riutta et al.* [2007b] monitored CO_2 exchange at an oligotrophic treeless fen within the mid-boreal region of Finland. Closed chambers were used to measure net ecosystem exchange over the growing seasons of 2001 – 2004 [*Riutta et al.*, 2007b]. The Siikaneva fen, also situated in the mid-boreal region, was intensely monitored from 2004 – 2006. Carbon dioxide fluxes [*Aurela et al.*, 2007; *Riutta et al.*, 2007a], and F_{CH4} [*Rinne et al.*, 2007; *Riutta et al.*, 2007a] were reported at the community scale using chamber techniques as well as at the ecosystem scale using closed-path EC systems.

Studies have also been performed across peatlands of northern Siberia. In late-July to mid-August, 1996, CO_2 fluxes were measured in the Taimyr Peninsula using chambers with a multi-channel gas exchange instrument over tussock, wet sedge, and low-centred polygonal tundra sites [*Sommerkorn et al.*, 1999; *Sommerkorn*, 2008]. *Corradi et al.* [2005] studied CO_2 and F_{CH4} over Arctic wet tussock grassland in the floodplain of the Kolyma River. A closed-path EC system was used to measure CO_2 fluxes over the growing season of 2002 and spring of 2003, while static chambers were used to measure

F_{CH4} from July – September 2002 [*Corradi et al.*, 2005]. *Petrescu et al.* [2008] compared F_{CH4} results from Kytalyk ombrotrophic mire in north-east Siberia to those obtained from the Stordalen mire in Sweden. A few short field campaigns of F_{CH4} were obtained during the summers of 2004-2006 at Kytalyk using closed chambers [*Petrescu et al.*, 2008]. *Wille et al.* [2008] measured F_{CH4} from a wet polygonal tundra site on Samoylov Island in the Lena River Delta, Central Siberia. A closed-path EC system was used to measure CO_2 fluxes, and incorporated tunable diode laser spectroscopy for measuring F_{CH4} from mid-summer to early winter in 2003, and early spring to mid-summer in 2004 [*Wille et al.*, 2008]. *Golovatskaya and Dyukarev* [2009] measured CO_2 fluxes at the Bakcharskoe oligotrophic bog in the southern boreal forest of western Siberia. Data was collected from 1999-2007, using chamber methods [*Golovatskaya and Dyukarev*, 2009].

Peatlands in Greenland were sampled intensively in terms of C fluxes from 1996 – 2005 at Zackenberg valley. Chambers with infrared gas analyzers, and a closed-path EC system were used to monitor CO_2 fluxes. Static chambers and an EC system incorporating tunable diode laser spectroscopy were used to monitor F_{CH4} [*Christensen et al.*, 2000; *Friborg et al.*, 2000; *Soegaard et al.*, 2000; *Grondahl et al.*, 2008]. *Mastepanov et al.* [2008] used automated chambers with the Fast Methane Analyzer (Los Gatos Research Inc.) to monitor F_{CH4} at a fen site at Zackenberg valley. Measurements were taken over the spring of 2006 and the growing season and fall of 2007 [*Mastepanov et al.*, 2008].

Several studies have been done in Alaska, in particular the Arctic Coastal Plain near Barrow and Toolik Lake Long Term Ecological Research (LTER) site in the zone of continuous permafrost. At Toolik Lake LTER site F_{CH4} were studied by *Schimel* [1995] over short campaign periods during the growing seasons of 1991-1993. The study site was a wet sedge meadow [*Schimel*, 1995]. *Verville et al.* [1998] studied both F_{CH4} and CO_2 fluxes at the same wet sedge meadow and a tussock tundra area at Toolik Lake LTER site. Static chambers were used to measure fluxes of both gases over the 1994 and 1995 growing seasons [*Verville et al.*, 1998]. *Oechel et al.* [1995] measured CO_2 fluxes over the growing seasons of 1991 and 1992 near Barrow over high and low centred polygons using both chambers and the aerodynamic method for *in situ* as well as ecosystem scale fluxes. These data were compared to C flux data collected in the early 1970's by the U.S. International Biological Program [*Oechel et al.*, 1995]. Recently, ecosystem scale F_{CH4} have been studied using EC in combination with the Fast Methane Analyzer (Los Gatos Research Inc.), as well as open-path EC for CO_2 fluxes over wet sedge tundra near Barrow, AK [*Zona et al.*, 2009].

In Canada, many studies have been performed on C fluxes in boreal peatlands that are within the discontinuous permafrost zone. However few studies have been done on C fluxes in Subarctic and Arctic zones within the continuous permafrost zone. *Bubier et al.* [1995] measured CH_4 emissions from a boreal peatland complex near Thompson, MB in the zone of discontinuous permafrost. The static chamber technique was used and monitored CH_4 emissions from May – September 1994. Boreal peatlands in the Athabasca region of northern Alberta have also been a focal point for C flux studies. *Glenn et al.* [2006] measured net ecosystem CO_2 exchange over an extreme rich fen and a poor fen. Measurements were taken using the EC technique over the 2004 growing season [*Glenn et al.*, 2006]. *Syed et al.* [2006] studied CO_2 fluxes for a moderately rich treed fen near Athabasca. A closed-path EC system was used to obtain ecosystem scale measurements from August 2003 – December 2004 [*Syed et al.*, 2006]. *Long et al.* [2009]

reported on CO_2 fluxes and F_{CH4} for the same moderately rich treed fen. Two EC towers were used; a closed-path EC system for measuring CO_2 and another incorporating tunable diode laser spectroscopy for measuring F_{CH4} from May – September 2007 [*Long et al.*, 2009]. *Moore* [1986] monitored CO_2 fluxes over 5 Subarctic fen sites near Schefferville, Quebec from June – October 1982 and June – September 1983. Measurements were made with chambers and incorporated the alkali absorption method [*Moore*, 1986]. *Lafleur and Humphreys* [2007] studied CO_2 fluxes over a mixed tundra site: heath tundra and shrub-hummock tundra near Daring Lake, Northwest Territories. An open-path EC system monitored CO_2 fluxes from late winter through the growing seasons of 2004 – 2006 [*Lafleur and Humphreys*, 2007]. To my knowledge, the only other C flux studies in Arctic peatlands within Canada have been within the Hudson Bay Lowlands near Churchill, Manitoba, with a Subarctic fen as one of the primary study sites.

1.6 Previous studies of CH_4 and CO_2 fluxes for a Subarctic fen at Churchill, MB

The Subarctic fen at Churchill, Manitoba was sampled intensely throughout the 1990's, with studies focussing primarily on CO_2 fluxes, with some work on F_{CH4}. Both chamber and flux gradient techniques were used during this time period.

Rouse et al. [1995] studied CH_4 emissions from 5 wetland sites at Churchill, MB, of which both the moist and wet sections of the fen were included, from mid-June – late August 1989 and mid-June – mid-September 1990. Measurements were performed using large static chambers (18 L) wrapped in aluminum foil to maintain the ambient temperature within the chambers, and samples were taken after an accumulation period of 24 hours, transported in vacutainers and analyzed with a gas chromatograph [*Rouse et al.,* 1995]. *Waddington et al.* [1998] measured CO_2 fluxes using both dynamic and static chambers with infrared gas analyzers. Measurements were taken from late May – early September 1996 [*Waddington et al.*, 1998]. *Churchill* [2007] measured F_{CH4} as well as respiration at the fen on a weekly basis from late May – late August 2006. Opaque static vented chambers were used to measure fluxes from each of the three dominant landscape units: hummocks, sedge-lawns and hollows, were transported in vacutainers and analyzed with a gas chromatograph [*Churchill*, 2007].

From mid-July – late August 2003, the flux gradient and Bowen ratio techniques were implemented to monitor ecosystem scale CO_2 emissions and energy balance over the fen [*Burton et al.*, 1996]. *Shreader et al.* [1998] studied CO_2 fluxes at the fen during the hot, dry summer of 1994 with the sedge community under water stress. The flux gradient and Bowen ratio techniques were used for CO_2 fluxes and energy balance [*Schreader et al.*, 1998]. *Griffis et al*. [2000b] attempted to scale-up chamber measurements of CO_2 fluxes to the ecosystem level and compare results with those obtained by the flux gradient technique for ecosystem-scale CO_2 flux determinations over the 1997 growing season. The chambers were clear, semi-dynamic, and incorporated an infrared gas analyzer [*Griffis et al.*, 2000b]. *Griffis et al.* [2000a] also reported on interannual variability of CO_2 fluxes from 1996 – 1999. The flux gradient and Bowen ratio station was used for these determinations [*Griffis et al.*, 2000a]. *Griffis and Rouse* [2001] incorporated CO_2 flux data measured from 1994 – 1999 at the fen into an empirical model for estimating net ecosystem CO_2 exchange. The model incorporated water balance, plant phenology and fitness, carbon allocation, plant growth, photosynthesis, respiration and meteorological parameters [*Griffis and Rouse*, 2001].

The first reported use of EC for measurement of ecosystem-scale fluxes of CO_2 at the fen was by *Lafleur et al.* [2001]. The station incorporated a closed-path infrared gas analyzer for measurement of [CO_2], and the Bowen ratio technique was used for energy balance measurements [*Lafleur et al.*, 2001]. The use of an open-path EC station for monitoring CO_2 fluxes was started in 2005 by *Papakyriakou et al.* [unpublished], and studied from 2007 – 2008 by *Swystun et al.* [unpublished].

1.7 Strengths and weaknesses of chamber and EC techniques

Chambers and micrometeorological techniques such as EC are both very important for understanding C fluxes from northern peatlands. The two techniques serve very different purposes and therefore have different strengths and weaknesses.

Chambers are very useful for determining small-scale *in-situ* measurements of CO_2 fluxes and F_{CH4}. This is very beneficial for studying C fluxes in northern peatlands that have varying microtopographical relief, as they provide a good understanding of the spatial variability of fluxes. Chambers are also relatively inexpensive to install, but can be more expensive if they are automated or incorporate infrared gas analyzers. Minimal training is required for personnel to use chambers in terms of sampling and maintenance. Chambers, however, are destructive to the ecosystem both during collar installation and with intensive manual sampling. Disturbance to the ecosystem is lessened when the chambers are automated. Also, one must consider how representative the flux values obtained from chamber sampling are when there is disturbance to the site. Another downfall is that the values obtained from chamber sampling are difficult to scale up to the ecosystem level when working in peatlands with varying microtopographic relief. Finally, samples collected in vacutainers can be expensive to ship south and process using gas chromatography.

The strengths of EC lie in that it measures ecosystem-scale fluxes on a continual basis over long periods of time. This is of considerable value in northern peatlands as we seek to understand how peatlands behave at the ecosystem-scale on a seasonal basis and which are logistically challenging to visit. The EC technique is less disruptive than chambers once the initial infrastructure is set-up, and flux footprints can cover several hundred meters. Eddy covariance measurements, however, cannot be scaled down in order to understand the variability of fluxes at the microtopographical scale. It is also very expensive to set-up an EC system and trained personnel are required to maintain the system and process the data.

1.8 Importance of ecosystem-scale measurements of CO_2 and CH_4 for northern peatlands

Ecosystem-scale measurements of C fluxes using techniques such as EC are of great importance for providing baseline data about how northern peatland ecosystems function, how productive they are, and what drives CO_2 fluxes and F_{CH4}. These data are also helpful in modelling C fluxes for different northern ecosystems to predict how they will change in the future with climate change. Because the GWP of CH_4 is 25 times greater than CO_2 [*Forster et al.*, 2007], even small CH_4 emission values become important contributions to GHG emissions.

Few studies have monitored ecosystem-scale measurements of F_{CH4} in northern peatlands in the Arctic and Subarctic which are underlain by permafrost [*Christensen et* *al.*, 2000; *Friborg et al.*, 2000; *Soegaard et al.*, 2000; *Heikkinen et al.*, 2002; *Grondahl et al.*, 2008; *Wille et al.*, 2008; *Zona et al.*, 2009] and only one study has been done within the boreal peatlands of Canada [*Long et al.*, 2009]. Therefore, there are many gaps in our knowledge of F_{CH4} for these ecosystems. At the Subarctic fen at Churchill, Manitoba, ecosystem-scale measurements of F_{CH4} using micrometeorological techniques such as EC have not been collected prior to this study. The use of chambers for understanding spatial variability of F_{CH4} [*Churchill*, 2007], as well as for upscaling and modelling, has been done [*Rouse et al.*, 2002; *Churchill*, 2007], but these estimates are based on short campaign periods. There is no continuous dataset of F_{CH4} for this study site. Without a continuous dataset, many questions are left to be answered. What happens to F_{CH4} on a diurnal and seasonal cycle? What happens to F_{CH4} when it rains? What are the dominant drivers behind F_{CH4}, i.e. water table, air and soil temperature, plant community type, stomatal conductance, plant health and phenology? Insight into some of these questions can be made based on chamber measurements, but some questions require one to consider F_{CH4} on a larger spatial scale. An important spatially related question for which we seek an answer is: Do emission bursts of CH_4 occur during transitional periods, i.e. spring-melt and fall freeze-up periods? And if emission bursts do occur, what are the drivers behind these bursts? Bubbles of gas have been observed to occur in early fall under thin layers of ice, and have also been found to occur within the thick winter ice. Due to the anaerobic nature of the fen, could it be that CH_4 is being trapped under and within ice during the freeze-up period until it can be released during spring-melt?

1.9 Study objectives

The aim of this study was to obtain ecosystem scale F_{CH4} for the Subarctic fen at Churchill, Manitoba over the 2008 growing season and fall freeze-up period, as well as from spring thaw – early fall of 2009. These measurements were the first of their kind for the study site, and the goal was to determining the contribution of F_{CH4} to the GHG budget. Firstly, we wished to observe the seasonal trend of F_{CH4} over the two consecutive growing seasons which had contrasting temperature and precipitation patterns. We then wished to focus on the spring period of 2009, observing how F_{CH4} was released during melt, and if CH_4 stored under ice would be released as a large burst of CH_4 to the atmosphere. If this phenomenon were to occur, future studies would need to consider this very important period in their measurements while incorporating the EC technique as other methods may not be able to capture emission bursts which are highly variable over the landscape. Lastly, we wished to examine soil temperature – F_{CH4} relations to determine the depth of soil having contributed to F_{CH4} during the spring melt period of 2009 for modelling.

1.10 References

ACIA, 2004. Impacts of a warming Arctic: Arctic climate impact assessment. Cambridge University Press, Cambridge, UK. 1042 p.

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J.P., Vesala, T., Tuittila, E.S., Rinne, J., Haapanala, S. and Laine, J., 2007. CO_2 exchange of a sedge fen in southern Finland – the impact of a drought period. Tellus Series B – Chemical and Physical Meteorology, 59: 862-837.

Burton, K.L., Rouse, W.R. and Boudreau, L.D., 1996. Factors affecting the summer carbon dioxide budget of a Subarctic wetland tundra. Climate Research, 6: 203-213.

Christensen, T.R., Friborg, T., Sommerkorn, M., Kaplan, J., Illeris, L., Soegaard, H., Nordstroem, C. and Jonasson, S., 2000. Trace gas exchange in a high-Arctic valley: 1. variations in CO_2 and CH_4 flux between tundra vegetation types. Global Biogeochemical Cycles, 14: 701-713.

Churchill, J.A., 2007. Spatial variation of soil methane and nitrous oxide emissions in Subarctic environments of Churchill, Manitoba. University of Manitoba, Winnipeg, Manitoba. Canada. 156 p., http://mspace.lib.umanitoba.ca/bitstream/1993/2453/1/Thesis.pdf

Corradi, C., Kolle, O., Walter, K., Zimov, S.A. and Schulze, E.D., 2005. Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. Global Change Biology, 11: 1910-1925.

Environment Canada, 1986. Wetlands in Canada: a valuable resource. Fact sheet 86-4. Lands Directorate, Ottawa, ON.

Forster, P., Ramaswamy, V., Artaxo, P., Bernsten, R., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Editors), Climate Change 2007: the Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, NY, USA. p. 129-234.

Friborg, T., Christensen, S., Hansen, U., Nordstroem, C. and Soegaard, H., 2000. Trace gas exchange in a high-Arctic valley: 2. landscape CH_4 fluxes measured and modeled using eddy correlation data. Global Biogeochemical Cycles, 14: 715-723.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C. and Zeng, N., 2006. Climate-carbon cycle feedback analysis: results from the (CMIP)-M-4 model intercomparison. Journal of Climate, 19: 3337-3353.

Glenn, A.J., Flanagan, L.B., Syed, K.H. and Carlson, P.J., 2006. Comparison of net ecosystem CO_2 exchange in two peatlands in western Canada with contrasting dominant vegetation, *Sphagnum* and *Carex*. Agricultural and Forest Meteorology, 140: 115-135.

Golovatskaya, E.A. and Dyukarev, E.A., 2009. Carbon budget of oligotrophic mire sites in the southern taiga of western Siberia. Plant Soil, 315: 19-34.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecological Applications, 1: 182-195.

Griffis, T.J. and Rouse, W.R., 2001. Modelling the interannual variability of net ecosystem CO_2 exchange at a Subarctic sedge fen. Global Change Biology, 7: 511-530.

Griffis, T.J., Rouse, W.R. and Waddington, J.M., 2000a. Interannual variability in the net CO_2 exchange in a Subarctic fen. Global Biogeochemical Cycles, 14: 1109-1121.

Griffis, T.J., Rouse, W.R. and Waddington, J.M., 2000b. Scaling net ecosystem CO_2 exchange from the community to landscape-level at a Subarctic fen. Global Change Biology, 6: 459-473.

Grondahl, L., Friborg, T., Christensen, T.R., Ekberg, A., Elberling, B., Illeris, L., Nordstrom, C., Rennermalm, A., Sigsgaard, C. and Sogaard, H., 2008. Spatial and inter-annual variability of trace gas fluxes in a heterogeneous high-Arctic landscape. Advances in Ecological Research, 40: 473-498.

Hargreaves, K.J., Fowler, D., Pitcairn, C.E.R. and Aurela, M., 2001. Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements. Theoretical and Applied Climatology, 70: 203-213.

Heide, O.M., Bush, M.G. and Evans, L.T., 1985. Interaction of photoperiod and giberellin on growth and photosynthesis of high-latitude Poa pratensis. Physiologia Plantarum, 65: 135 – 145.

Heikkinen, J.E.P., Maljanen, M., Aurela, M., Hargreaves, K.J. and Martikainen, P.J., 2000. Carbon dioxide and methane dynamics in a sub-arctic peatland in northern Finland. Polar Research, 21: 49-62.

Hendriks, D.M.D., Dolman, A.J., van der Molen, M.K. and van Huissteden, J., 2008. A compact and stable eddy covariance set-up for methane measurements using off-axis integrated output spectroscopy. Atmospheric Chemistry and Physics, 8: 431-443.

Hendriks, D.M.D., van Huissteden, J., Dolman, A.J. and van der Molen, M.K., 2007. The full greenhouse gas balance of an abandoned peat meadow. Biogeosciences, 4: 411-424.

Kettles, I.M. and Tarnocai, C., 1999. Development of a model for estimating the sensitivity of Canadian peatlands to climate warming. Geographie Physique et Quaternaire, 53: 323-338.

Komulainen, V.M., Tuittila, E.S., Vasander, H. and Laine, J., 1999. Restoration of drained peatlands in southern Finland: initial effects on vegetation change and CO_2 balance. Journal of Applied Ecology, 36: 634-648.

Lafleur, P.M., Griffis, T.J. and Rouse, W.R., 2001. Interannual variability in net ecosystem CO_2 exchange at the Arctic treeline. Arctic Antarctic and Alpine Research, 33: 149-157.

Lafleur, P.M. and Humphreys, E.R., 2007. Spring warming and carbon dioxide exchange over low Arctic tundra in central Canada. Global Change Biology, 14: 740-756.

Lai, D.Y.F., 2009. Methane dynamics in northern peatlands: a review. Pedosphere, 19: 409-421.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G., 2008. Peatlands and the carbon cycle: from local processes to global implications. Biogeosciences, 5: 1475-1491.

Long, K.D., Flanagan, L.B. and Cai, T., 2009. Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. Global Change Biology, doi: 10.111/j.1365-2486.2009.02083.x.

Mastepanov, M., Sigsgaard, C., Dlugokencky, E.J., Houweling, S., Strom, L., Tamstorf, M.P. and Christensen, T.R., 2008. Large tundra methane burst during onset of freezing. Nature, 456: 628-630.

McGuire, A.D., Anderson, L.G., Christensen, T.R., Dallimore, S., Guo, L.D., Hayes, D.J., Heimann, M., Lorenson, T.D., Macdonald, R.W. and Roulet, N., 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs, 79: 523-555.

Mikkela, C., Sundh, I., Svensson, B.H. and Nilsson, M., 1995. Diurnal variation in methane emission in relation to the water table, soil temperature, climate and vegetation cover in a Swedish acid mire. Biogeochemistry, 28: 93-114.

Moore, T., 1986. Carbon dioxide evolution from Subarctic peatlands in eastern Canada. Arctic and Alpine Research, 18: 189-193.

Morrisey, L.A., Zobel, D.B. and Livingston, G.P., 1993. Significance of stomatal control on methane release from Carex-dominated wetlands. Chemosphere, 26: 339-355.

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P. and Lindroth, A., 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes. Global Change Biology, 14: 2317-2332.

NWWG, 1988. Wetlands of Canada / by National Wetlands Working Group, Canada Committee on Ecological Land Classification. Ottawa, ON.

NWWG, 1997. The Canadian Wetland Classification System: Second Edition. Wetlands Research Centre, University of Waterloo, Waterloo, ON.

Oechel, W.C., Vourlitis, G.L., Hastings, S.J. and Bochkarev, S.A., 1995. Changes in Arctic CO_2 flux over two decades: effects of climate change at Barrow, Alaska. Ecological Applications, 5: 846-855.

Petrescu, A.M.R., Van Huissteden, J., Jackowicz-Korczynski, M., Yurova, A., Christensen, T.R., Crill, P., Backstrand, K. and Maximov, T.C., 2008. Modelling CH_4 emissions from Arctic wetlands: effects of hydrological parameterization. Biogeosciences, 5: 111-121.

Reddy, K.M. and DeLaune, R.D., 2008. Ch 16: Wetlands and Global Climate Change, In: Biogeochemistry of Wetlands: Science and Applications. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, p. 559-621.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.P., Tuittila, E.S. and Vesala, T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus Series B – Chemical and Physical Meteorology, 59: 449-457.

Riutta, T., Laine, J., Aurela, M., Rinne, J., Vesala, T., Laurila, T., Haapanala, S., Pihlatie, M. and Tuittila, E.S., 2007a. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. Tellus Series B – Chemical and Physical Meteorology, 59: 838-852.

Riutta, T., Laine, J. and Tuittila, E.S., 2007b. Sensitivity of CO_2 exchange of fen ecosystem components to water level variation. Ecosystems, 10: 718-733.

Rouse, W.R., Bello, R.L., D'Souza, A., Griffis, T.J. and Lafleur, P., 2002. The annual carbon budget for fen and forest in a wetland at Arctic treeline. Arctic, 55: 229-237.

Rouse, W.R., Holland, S. and Moore, T.R., 1995. Variability in methane emissions from wetlands at northern treeline near Churchill, Manitoba, Canada. Arctic and Alpine Research, 27: 146-156.

Schimel, J.P., 1995. Plant transport and methane production as controls on methane flux from Arctic wet meadow. Biogeochemistry, 28: 183-200.

Schreader, C.P., Rouse, W.R., Griffis, T.J., Boudreau, L.D. and Blanken, P.D., 1998. Carbon dioxide fluxes in a northern fen during a hot, dry summer. Global Biogeochemical Cycles, 12: 729-740.

Scott, G.A.J., 1995. Canada's vegetation: a world perspective. McGill-Queen's University Press, Montreal & Kingston, ON. 361 pp.

Soegaard, H., Nordstroem, C., Friborg, T., Hansen, U., Christensen, S. and Bay, C., 2000. Trace gas exchange in a high-Arctic valley: 3. integrating and scaling CO_2 fluxes from canopy to landscape using flux data, footprint modeling, and remote sensing. Global Biogeochemical Cycles, 14: 725-744.

Sommerkorn, M., 2008. Micro-topographical patterns unravel controls of soil water and temperature on soil respiration in three Siberian tundra systems. Soil Biology & Biogeochemistry, 40: 1792-1802.

Sommerkorn, M., Bolter, M. and Kappen, L., 1999. Carbon dioxide fluxes of soils and mosses in wet tundra of Taimyr Peninsula, Siberia: controlling factors and contribution to net system fluxes. Polar Research, 18: 253-260.

Strack, M., Kellner, E. and Waddington, J.M., 2006a. Effect of entrapped gas on peatland surface level fluctuations. Hydrological Processes, 20: 3611-3622.

Strack, M., Waller, M.F. and Waddington, J.M., 2006b. Sedge succession and peatland methane dynamics: a potential feedback to climate change. Ecosystems, 9: 278-287.

Svensson, B.H., Christensen, T.R., Johansson, E. and Oquist, M., 1999. Interdecadal changes in CO_2 and CH_4 fluxes of a Subarctic mire: Stordalen revisited after 20 years. Oikos, 85: 22-30.

Syed, K.H., Flanagan, L.B., Carlson, P.J., Glenn, A.J. and Van Gaalen, K.E., 2006. Environmental control of net ecosystem CO_2 exchange and carbon balance in a treed moderately rich fen in northern Alberta. Agricultural and Forest Meteorology, 140: 97-114.

Tarnocai, C. 1984. Peat resources of Canada. Land Resource Research Institute, Research Branch, Agriculture Canada, Ottawa, ON, Canada.

Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. Global and Planetary Change, 53: 222-232.

Tarnocai, C., Ping, C.L., and Kimble, J., 2007. Carbon Cycles in the Permafrost Region of North America, In King, A.W., Dilling, L., Zimmerman, G.P., Fairman, D.M., Houghton, R.A., Marland, G., Rose, A.Z., and Wilbanks, T.J. (Editors) - The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, Chapter 12, pp. 127-138.

Veenendaal, E.M., Kolle, O., Leffelaar, P.A., Schrier-Uijl, A.P., Van Huissteden, J., Van Walsem, J., Moller, F. and Berendse, F., 2007. CO_2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. Biogeosciences, 4: 1027-1040.

Verville, J.H., Hobbie, S.E., Chapin, F.S. and Hooper, D.U., 1998. Response of tundra CH_4 and CO_2 flux to manipulation of temperature and vegetation. Biogeochemistry, 41: 215-235.

Waddington, J.M., Griffis, T.J. and Rouse, W.R., 1998. Northern Canadian wetlands: net ecosystem CO_2 exchange and climate change. Climatic Change, 40: 267-275.

Wille, C. Kutzbach, L., Sachs, T., Wagner, D. and Pfeiffer, E.M., 2008. Methane emission from Siberian Arctic polygonal tundra: eddy covariance measurements and modeling. Global Change Biology, 14: 1395-1408.

Yu, K.W. and Patrick, W.H., 2004. Redox window with minimum global warming potential contribution from rice soils. Soil Science Society of America Journal, 68: 2086-2091.

Zona, D., Oechel, W.C., Kochendorfer, J., Paw U, K.T., Salyuk, A.N., Olivas, P.C., Oberbauer, S.F. and Lipson, D.A., 2009. Methane fluxes during the intiation of a large-scale water table manipulation experiment in the Alaskan Arctic tundra. Global Biogeochemical Cycles, 23: GB2013, doi: 10.1029/2009GB003487.

2. EDDY COVARIANCE MEASUREMENTS OF METHANE FLUX IN A SUBARCTIC FEN WITH EMPHASIS ON SPRING-MELT PERIOD

2.1 Introduction

Northern peatlands cover 3.5×10^6 km^2 of the circumpolar north and store approximately 455 Pg of carbon (C), one third of the world's soil organic C [*Gorham*, 1991]. A substantial portion of northern peatlands are within Canada, extending over 1.1×10^6 km^2 and containing about 150 Pg C [*Tarnocai*, 2006]. Approximately 112 Pg C [*Tarnocai et al.*, 2007] is stored within Canadian peatlands that are within permafrost regions; 37% of all Canadian peatland area [*Tarnocai*, 2006]. Terrestrial regions of the Arctic, including peatlands, have provided an estimated net uptake of 300 – 600 Tg C y^{-1} since 1975 [*McGuire et al.*, 2009]. However, the benefit as a sink of carbon dioxide (CO_2) which is active in radiative forcing of the atmosphere, is offset by the emission of another gas causing radiative forcing of the atmosphere, methane (CH_4), of 30 – 100 Tg CH_4 y^{-1} for the terrestrial Arctic [*McGuire et al.*, 2009].

Methane is emitted naturally from wetlands and peatlands, but it is anthropogenic emissions from sources such as rice paddies, landfills, ruminant livestock, manure storages and natural gas exploitation that have caused much of the substantial increase from pre-industrial atmospheric concentrations of 715 ppb to the current 1774 ppb [*Forster et al.*, 2007]. Methane in the atmosphere is oxidized by reaction with hydroxyl radicals, increasing water vapour and CO_2 levels in the stratosphere, and decreasing ozone concentrations in the troposphere [*Forster et al.*, 2007; *Reddy and DeLaune*, 2008]. Methane is 25 times more effective at radiative forcing of the atmosphere than CO_2

[*Forster et al.*, 2007]. Thus, the implications of C loss from CH_4 emissions are overshadowed by the radiative forcing of the atmosphere caused by this gas.

Methane production and consumption is governed by the biological processes of methanogenesis and methanotrophy. Methanogenesis is the production of CH_4 which occurs in anoxic environments at a redox potential (Eh) < -200 mV by methanogenic bacteria belonging to the Kingdom Archaea, that primarily use the simple reduced organic acid acetate (CH_3COO^-), or CO_2 as terminal electron acceptors during respiration [*Yu and Patrick*, 2004; *Lai*, 2009]. The anaerobic condition of peatlands is generally determined by water table height from the soil surface in which water impedes diffusion of atmospheric oxygen to the soil [*Limpens et al.*, 2008]. Methanotrophy is the oxidation of CH_4 to CO_2 during respiration by bacteria in the γ and α subdivisions of the Proteobacteria [*Kolb*, 2009]. Methanotrophy occurs in oxic environments at Eh > -200 mV, which in peatlands, is at the peat-water interface and around roots (rhizosphere) [*Yu and Patrick*, 2004]. Methanotrophy and methanogenesis are in near balance with the former consuming about 90% of CH_4 emitted annually from anthropogenic and natural sources [*Forster et al.*, 2007; *Reddy and DeLaune*, 2008].

The other dominant environmental controllers of the rates of methanogenesis and methanotrophy in peatlands are temperature and organic C sources of reductants [*Moore and Dalva*, 1997; *Moore et al.*, 1998]. Temperature influences both processes by increasing the rate of metabolic activity in soil microbes as soil temperatures increase, up to a maximum of 25 °C [*Dunfield et al.*, 1993; *Lai*, 2009], thus increasing decomposition. Therefore increasing soil temperature as a response to climate change is anticipated to have considerable impact on CH_4 flux (F_{CH4}) [*Reddy and DeLaune*, 2008; *Lai*, 2009].

Organic C sources of reductants are determined largely by amount and degradability of plant residues and roots which turn over throughout the growing season. Peat from northern peatlands is a source of slowly available and degradable organic C which supplies energy for methanogenesis [*Christensen et al.*, 1996].

The Coupled Climate-Carbon Cycle Model Intercomparison Project (C^4MIP) predicts an average global temperature increase of 0.1 – 1.5°C by the year 2100 [*Friedlingstein et al.*, 2006; *McGuire et al.*, 2009]. For the Arctic, the temperature increase is predicted to be as high as 3 – 5°C by the end of the 21st century [*ACIA*, 2004]. How the predicted increase in north circumpolar temperature will affect northern peatlands, in particular those that are underlain by permafrost, remains unknown. Short-term effects may include melting permafrost, and increased emissions of CO_2 and CH_4. These increased emissions will enhance the greenhouse effect through greater radiative forcing of the atmosphere, which in turn can melt permafrost, creating a positive feedback mechanism for global warming [*Turetsky et al.*, 2002]. It is also likely that increased temperatures will cause more hydrologic connections of land areas resulting in greater drainage and water table draw down, thus creating more aerobic soils [*Gorham*, 1991] and decreasing F_{CH4} while increasing CO_2 emissions to the atmosphere. It is therefore important to study northern peatlands in order to understand how these sensitive ecosystems respond to temperature, water table height, and plant community composition in order to predict what future conditions will lead to emissions of CH_4 and CO_2.

Previous studies of F_{CH4} in northern peatlands have examined the effects of water table height [*Bubier and Moore*, 1994; *Mikkela et al.*, 1995; *Christensen et al.*, 2003; *Long et al.*, 2009], temperature [*Verville et al.*, 1998; *Hargreaves et al.*, 2001; *Rinne et* *al.*, 2007; *Wille et al.*, 2008; *Long et al.*, 2009], plant communities, in particular hydrophytes with aerenchyma tissues for plant-mediated transport of rhizosphere gases, including CH_4 to the atmosphere [*Mikkela et al.*, 1995; *Schimel*, 1995; *Syed et al.*, 2006; *Long et al*., 2009], as well as diurnal patterns in F_{CH4} [*Mikkela et al.*, 1995; *Suyker et al.*, 1996; *Rinne et al.*, 2007; *Hendriks et al.*, 2008; *Long et al.*, 2009]. Many studies have been performed during the period of peak productivity of northern peatland vegetation (mid-summer) [*Verville et al.*, 1998; *Svensson et al.*, 1999; *Updegraff et al.*, 2001; *Grondahl et al.*, 2008]. Therefore, a fairly robust understanding of F_{CH4} and their drivers during the growing season have been developed. However, there is still much unknown about F_{CH4} over the winter and shoulder seasons of spring-melt and fall freeze-up. These three seasons combined encompass 8 – 10 months of the year in Subarctic and Arctic environments, and therefore must be of consideration in annual C and net greenhouse gas (GHG) emission budgets.

The shoulder seasons have become of particular interest in recent years, as emission bursts have been reported during spring-melt and fall freeze-up periods. *Tokida et al.* [2007], described episodic release of CH_4 from bubbles in ice overlying an ombrotrophic bog in Japan during spring-melt. It was suggested that CH_4 released through ebullition from peat had become trapped within ice underlying the snowpack during freeze-thaw cycles in the previous fall and winter [*Tokida et al.*, 2007]. *Hargreaves et al.* [2001], reported spring-melt F_{CH4} bursts from a Finnish minerotrophic flark fen dominated by graminoids. Top-down melting of the snow and ice occurred, and bubbles were observed to be released through holes and cracks in ice residing above the sediment surface of the fen. Fall freeze-up F_{CH4} bursts have also been reported to occur during freeze-thaw cycles in the same Finnish flark fen [*Hargreaves et al.*, 2001], and in a graminoid fen in Greenland underlain by permafrost [*Mastepanov et al.*, 2008]. Methane entrapped within the peat in the winter is speculated to be released due to a top-down, bottom-up freezing of the soil in the fall which creates a trapped unfrozen anaerobic zone that releases CH_4 through the aerenchyma tissue of plants [*Kim et al.*, 2007; *Mastepanov et al.*, 2008]. Our understanding of shoulder season fluxes is still rudimentary, and considerable effort is required to understand ecosystem scale F_{CH4} for northern peatlands during these periods.

Studies of F_{CH4} using chamber methods have been successful in capturing *in situ* fluxes and are valuable for understanding the spatial variability of emissions within ecosystems with varying microtopographical relief and vegetation [*Churchill*, 2007; *Grondahl et al.*, 2008]. Although these determinations have their merits, chamber methods introduce many biases. Limited replication may not allow all variability within the site to be accounted for. This is particularly important when one considers the spatial-temporal irregularity of ebullition events within peatlands [*Bartlett and Harriss*, 1993]. In addition, visiting chambers to sample gas results in killing surface vegetation and compacting peat surrounding chamber sites, as well as microclimatic alterations within and around the collar of chambers, affecting the magnitude of F_{CH4} measured [*Denmead*, 2008]. Finally, winter and spring-time chamber flux measurements can be extremely difficult and unattainable during melt.

Micrometeorological techniques such as flux gradient and eddy covariance (EC) make use of tower-based measurements of gas concentrations and wind velocities to estimate fluxes over a landscape, capturing the spatial-temporal variability of the ecosystem while being less disruptive to the study area [*Denmead*, 2008]. These techniques also have the capacity to measure fluxes at high frequencies over campaign periods or on a continual basis. Therefore, F_{CH4} studies from northern peatlands with varying microtopographical relief are better suited to tower-based micrometeorological techniques.

The objectives of this study were to determine ecosystem scale F_{CH4} from a eutrophic Subarctic fen, to understand how F_{CH4} compared over two consecutive growing seasons with contrasting temperature and precipitation patterns, if there was over-winter stored CH_4 that was released as a pulse during the melt period and the depth of soil having contributed to F_{CH4} during spring-melt through examination of soil temperature - F_{CH4} relations.

2.2 Methods

2.2.1 Site description

The study site is a eutrophic palsa fen (fen) [*NWWG*, 1997] located southeast of the Town of Churchill, MB and approximately 12 km south of the Churchill Northern Studies Centre (CNSC) along Twin Lakes Road (58° 39' 57" N, 93° 49' 48" W) (Fig. 1). It is situated within the forest-tundra ecotone, which is a transitional zone extending approximately 10 km inland from the Hudson Bay coastline [*Kershaw and McCulloch*, 2007], and within the zone of continuous permafrost [*Brown*, 1970]. The fen hosts three dominant landscape units: hummocks, sedge-lawns, and hollows. The hummocks and sedge-lawns have 30 – 40 cm of peat over carbonate-rich glaciomarine sediments [*Scott*, 1995; *Rouse et al.*, 2002]. The active layer extends to greater than 1.5 m depth.

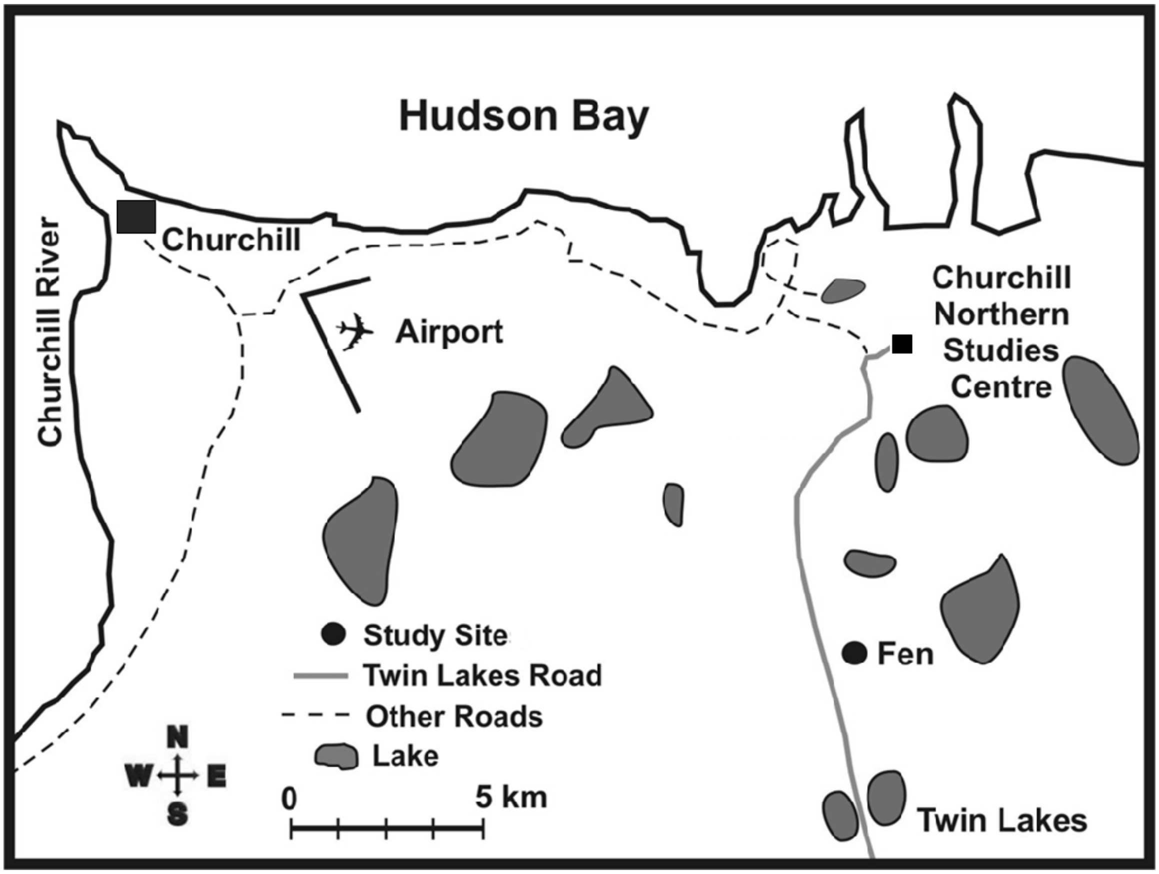


Figure 1: Map of the Churchill area and the fen study site in relation to the Town of Churchill, MB, the Churchill Northern Studies Centre, and Twin Lakes Road.

The sedge-lawn landscape unit is the most extensive, covering approximately 55% of the fen [*Raddatz et al.*, 2009] and is dominated by the sedge *Carex aquatilis* Wahlenb., as well as other *Carex* spp., the grasses *Eriophorum* spp., *Calamagrostis* spp., and *Arctagrostis latifolia* (R. Br.) Griseb., rushes *Juncus spp.*, horsetail *Equisetum variegatum* Schleich. ex F. Weber & D. Mohr, and an understory of the pseudocalliergon moss, *Pseudocalliergon turgescens* (Jensen) Loeske. The sedge-lawn landscape unit is at the water table soil surface interface at an elevation of 16.56 m (sd = 0.405, n = 29), with the *P. turgescens* being submersed during periods of high water table (often June, September and October), and exposed during periods of low water table (often July and August).

The vegetation of hummocks is dominated by the lichens *Cladina stellaris* (Opiz) Brodo and *C. rangiferina* (L.) Nyl., the moss *Dicranum elongatum* Schwaegr., as well as heath vegetation *Betula glandulosa* Michx., *Salix arctophila* Cock. ex Heller, *Ledum palustre* L. ssp.*decumbens* (Aiton) Hultén, *Andromeda polifolia* L., *Rhododendron lapponicum* (L.) Wahlenb., *Vaccinium vitis-idaea* L. ssp. *minus* (Lodd.) Hultén, and *V. uliginosum* L. The hummocks are mounds that rise above the level of the sedge-lawn surface by 0.44 m (sd = 0.244, n = 12) and are therefore drier.

The hollows are depressions which have mats of *P. turgescens*, and partially decomposed peat material at their base, overlying a mineral subtrate. The hollows are typically filled with water, with the exception of during extreme drought periods. The hollows extend to 0.55 m (sd = 0.127, n = 3) below the level of the sedge-lawn surface. Some of the deep hollows have a cobble layer of carbonate rock exposed at their base.

The water table for the fen fluctuates throughout the growing season, with an annual variation of 15 – 20 cm (Fig. 2). The maximum water table height usually occurs just after spring snow melt. During the study period snow melt occurred from May 23 – 26, 2008 (day of year (DOY) 144 – 147) but was delayed by approximately three weeks in 2009, occurring from June11 – 13 (DOY 162 – 164). The fen was snow and ice covered by October 26, 2008 (DOY 298) and October 13, 2009 (DOY 286).

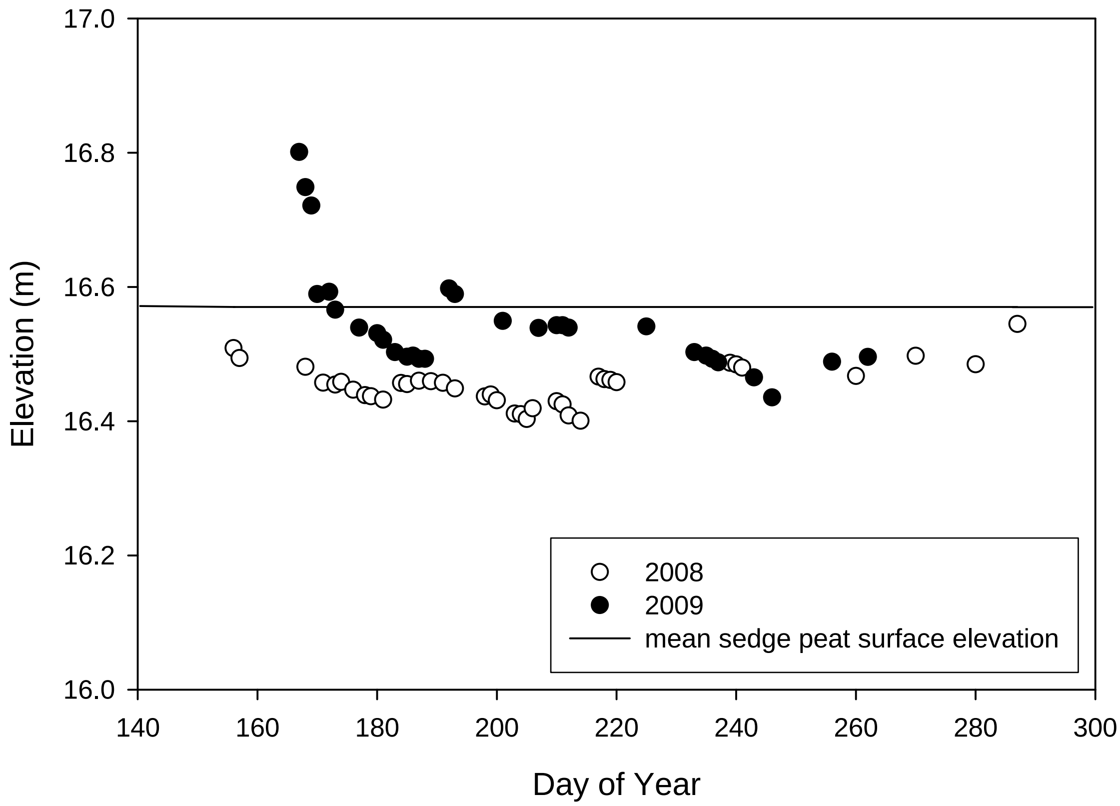


Figure 2: Mean water table height for 2008 (mean SE = 0.181; n = 3) and 2009 (mean SE = 0.179; n = 3) and the mean sedge peat surface elevation (n = 29).

Because *C. aquatilis* is the principal vascular plant at the fen and can facilitate CH_4 transport to the atmosphere [*Schimel*, 1995; *Syed et al.*, 2006], the phenological state of the plant was observed throughout the growing seasons. New shoots emerged on June 16, 2008 (DOY 168) and June 30, 2009 (DOY 181). Flowering occurred July 3, 2008 (DOY 185) and much later on July 26, 2009 (DOY 207). Senescence occurred August 26, 2008 (DOY 239) and August 31, 2009 (DOY 243). All dates are approximations based on in-field observations and examination of photographs taken every week at the site.

2.2.2 EC flux station set-up

A gas flux monitoring station was established within the fen at a location 300 m east of Twin Lakes Road in June of 2008 (Fig. 1; 58° 39’ 53” N, 93° 49’ 52” W). The station was capable of determinations of F_{CH4} and net ecosystem exchange of CO_2 (*NEE*), as well as sensible heat (*H*) and water vapour (*LE*) fluxes. The station was comprised of four systems; power generation, power storage, EC flux and meteorological monitoring (Fig. 3).

The station operated remotely without connection to an electrical grid by incorporating wind, solar, and gas power generation. Wind generated power was provided in 2008 by a Model 200 Whisper Wind Generator (Southwest Windpower Inc., Flagstaff, AZ) at 7.5 m. The Whisper 200 had three blades providing a rotor diameter of 2.7 m, and required a minimum wind velocity of 3.1 m s^{-1} to generate power. The rated power was 1000 W at a wind velocity of 11.6 m s^{-1}. Unregulated power from the Whisper 200 was brought into a charge controller (Southwest Windpower Inc.) and regulated to 24 VDC before charging the battery bank. Solar power was provided by five photovoltaic (PV) panels, with a total combined rating of 500 W, attached to the south face of the scaffold. Solar power was regulated to 24 VDC using two photovoltaic charge controllers (Xantrex, Burnaby, BC; Blue Sky, Vista, CA, USA) before being delivered to the battery bank. Power was supplemented with a EU2000i gas generator (Honda Inc.). The gas generator was operated intermittently when the battery bank was below 24 VDC. Power was stored using a bank of high-capacity deep-cycle batteries. Twelve 370 Ahr, 6 V, flooded lead-acid deep-cycle batteries (East Penn Manufacturing Co., Lyon Station, PA) were wired to create a 24 V battery bank (Fig. 2b). Battery power was converted to 110

VAC using an FX Series inverter/charger (Outback Power Systems, Arlington, WA) to power the flux station.

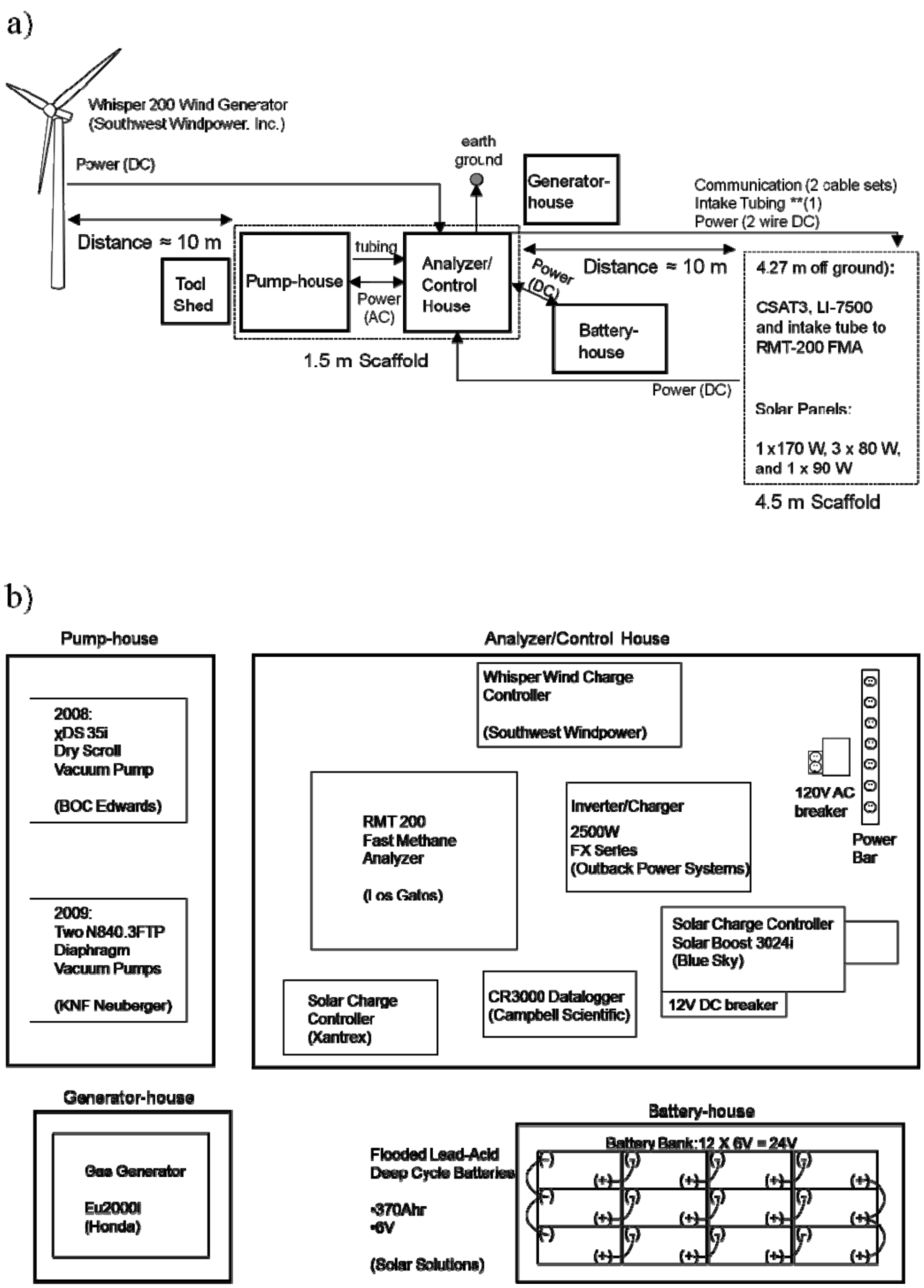


Figure 3: Schematic of the eddy covariance flux measurement station, (a) station systems, and (b) detail of enclosures.

2.2.3 EC flux monitoring equipment

Methane concentrations [CH_4] were determined using a closed-path RMT-200 Fast Methane Analyzer (Los Gatos Research Inc., Mountain View, CA) utilizing off-axis integrated cavity output spectroscopy (off-axis ICOS). The RMT-200 used a diode laser to produce a near-infrared beam with a $\lambda = 1.65$ μm. The beam was introduced at an angle into a stainless steel cavity having two 1-m-radius-of-curvature path and 5.08 cm diameter highly reflective mirrors which created a path-length of $2 – 20x10^3$ m. Sampled atmosphere was introduced into the cavity, and the detector measured the fractional absorption of the beam within the cavity, and thus provided an absolute [CH_4] determination [*Baer et al.*, 2002; *Hendriks et al.*, 2008]. Because of this technique, the analyzer was self-calibrating. The RMT-200 measurement range was 0.1 – 25 ppmv with <1% uncertainty, having a response time within the cavity of 0.05 s when operated in external pump mode [*Los Gatos Research,* 2009]. Determinations of [CH_4] were performed at 10 Hz and the pressure in the cavity was maintained at 142.5 Torr.

Sample air was passed from a point of intake, 4.27 m above the fen surface, to the RMT-200 using an 18 m semi-clear extreme-temperature PTFE-Teflon intake tube (6.35 mm i.d.) (Zeus Inc., Orangeburg, SC). A 7 μm inline filter (Swagelok, Solon, OH) and PVC 3/8" NPT 80 Mesh Strainer (Cole Parmer, Vernon Hills, IL) filtered particles from the sample stream. An XDS 35i dry vacuum scroll pump (Edwards, Crawley, West Sussex, UK) was used during the 2008 field season to draw air through the RMT-200 at a flow rate of 28.5 L min^{-1}. The lag from sample intake to analysis was 1.2 s. In 2009, the XDS 35i dry vacuum scroll pump failed and was replaced prior to the start of measurements with two LABOPORT N840.3 FTP diaphragm vacuum pumps (KNF

Neuberger, Inc., Trenton, NJ) connected in parallel to provide a system flow rate of 4.6 L min^{-1} and a lag time of 7.5 s.

A LI-7500 open-path CO_2/H_2O analyzer (LI-COR Biosci., Lincoln, NE) was used to determine CO_2 concentrations [CO_2]. An infrared source within the head of the LI-7500 discharged a beam through a 12.5 cm open-air path and a detector measured absorption at λ = 4.26 µm to provide an absolute [CO_2]. The LI-7500 was mounted at a 35° angle facing north at a height of 4.27 m above the peat surface.

A CSAT3 3-dimensional ultrasonic anemometer-thermometer (Campbell Sci., Logan, UT) was mounted 4.27 m above the peat surface so that the suspension arm holding the anemometer faced due north. The CSAT3 was 33 cm from the LI-7500 on the east side. The CSAT3 measured wind velocities in three non-orthogonal axes to determine wind velocities in three orthogonal directions: streamwise (u_x), crosswind (u_y), and vertical (u_z). In combination with gas concentration measurements, 3-dimensional velocities were used to calculate the vertical transfer of gases (F_{CH4} and *NEE*).

Concentrations of CH_4, molar density of CO_2, as well as 3-dimensional wind velocities were recorded at a frequency of 10 Hz on a CR3000 datalogger (Campbell Sci.). The RMT-200 was operated for campaign periods of 2 – 12 h, while [CO_2] and 3-dimensional wind velocities were recorded nearly continuously during both field seasons.

2.2.4 EC measurements

The EC method was used to determine F_{CH4} and *NEE* over the two field seasons, June 29 – October 18, 2008 (DOY 181 – 292), and May 30 – September 20, 2009 (DOY 150 – 263), at the fen. The EC method is a statistical technique which determined flux (*F)* based on the covariance between vertical wind velocity (w) and the mixing ratio of a study gas ($s = \rho_s/\rho_a$ where ρ_s is the density of the study gas and ρ_a is the density of air) (1):

$$F = \overline{\rho_a} \cdot \overline{w's'} \qquad (1)$$

where overbars represent a 30 minute time averaged period, and primes represent instantaneous deviations from the mean [*Baldocchi*, 2003]. However, sensors such as the LI-7500 measure [CO_2] as a molar density rather than a mixing ratio, so the flux equation was adjusted as follows (2):

$$F = \overline{w'\rho_s'} + \overline{w} \cdot \overline{\rho_s} \qquad (2)$$

where the mean vertical wind velocity ($\overline{w}$) is not equal to zero due to air density fluctuations caused by non-uniformity of atmospheric air pressure, temperature (T) and humidity (ρ_v) [*Webb et al.*, 1980]. The Webb-Pearman-Leuning (WPL) correction was used to correct for air density fluctuations (3):

$$F = \overline{w'\rho_s'} + \frac{m_a}{m_v} \cdot \frac{\overline{\rho}_s}{\overline{\rho}_a} \cdot \overline{w'\rho_v'} + \left(1 + \frac{\overline{\rho}_v m_a}{\overline{\rho}_a m_v}\right) \cdot \frac{\overline{\rho}_s}{\overline{T}} \cdot \overline{w'T'} \qquad (3)$$

where m_a is the molecular mass of air, and m_v is the molecular mass of water vapour [*Webb et al.*, 1980]. Because the closed path RMT-200 analyzer system removed rapid temperature fluctuations of the sample stream, only the humidity portion (second term in Equation 3) of the WPL correction was made to F_{CH4}. The LI-7500 is an open-path analyzer, so both humidity and temperature portions of the WPL correction were made to *NEE* measurements. The convention used for flux measurements in this study defines upward fluxes as positive and downward fluxes as negative.

2.2.5 Environmental measurements

A meteorological station was present, 250 m east of Twin Lakes Road, and 25 m south of the EC flux station. Air temperature (Tair) was measured using HMP45C Temperature/Relative Humidity Probes (Vaisala Inc., Woburn, MA) at 3.9 m and 1.8 m height. Horizontal wind speed and direction were measured with a Model 05103 propeller wind monitor (R.M. Young Co., Traverse City, MI) at a height of 4 m. Photosynthetically active radiation (PAR) was measured with an upward facing PAR Lite sensor (Kipp & Zonen, Bohemia, NY) at a height of 1 m. Tair, wind speed and PAR were recorded every 3 s, averaged over a 30-min period and logged using a CR5000 datalogger (Campbell Sci.). Rainfall was measured using a TR-525M tipping bucket rain gauge (Texas Electronics Inc., Dallas, TX), and recorded every half hour using a CR23X datalogger (Campbell Sci.). Soil temperature (Tsoil) profiles were determined using Type T copper-constantan (Omega Engineering Inc., Laval, QC) thermocouples (TC) along the length of two wooden dowels driven into the peat to provide soil temperatures at 10, 20, 30, 40, 50, and 60 cm depths. Dowels were driven into the peat at a sedge-lawn and a hummock position and the temperatures for a depth averaged. In addition, three TCs were placed at 5 cm in positions of hummocks, sedge-lawns and hollows and wired in parallel to provide an average ecosystem near-surface temperature. The Tsoil data were logged every 3 s and averaged every 30 min using the CR23X datalogger.

2.2.6 Data analysis

2.2.6.1 EC flux generation

Half-hourly EC flux determinations were performed using MATLAB (R2007a, The Math Works Inc., Natick, MA) user-defined functions. Spikes in the data set were removed based on thresholds for each signal set to identify single spurious values. Covariance measurements of [CH_4] and [CO_2] with *w* were maximized half-hourly with calculated delays in the user-defined MATLAB functions. However, as the flux becomes very small, calculating delays becomes uncertain. Hence, during the pre-thaw period of 2009 when [CH_4] and [CO_2] were minimal, a fixed 7.5 s delay equal to the lag time of the pumps and tubing was implemented for F_{CH4} determinations, and a fixed delay of 0.2 s was used for *NEE* determinations. The F_{CH4} was not corrected for high frequency losses as sample gas traversed the sample tube to the RMT-200. High frequency losses caused by the sample tube were estimated to be less than 1% of the total flux based upon integrations of the co-spectra of F_{CH4} and *H*. This was true for both pump systems. Raw cross-products were then corrected so that the mean vertical *w* was zero through coordinate rotations [*Tanner and Thurtell*, 1969], before applying Equation 3.

Under cold conditions, heat emitted from the LI-7500 affects the density of air within the sensory path of the instrument [*Burba et al.*, 2008], and thus provides erroneous *NEE* as false uptake of CO_2 by the ecosystem. Surface heating corrections are advised when the LI-7500 is mounted in the vertical position, as this will result in the greatest surface heating [*Burba et al.*, 2008]. However, the LI-7500 at the fen was mounted on a 35° angle towards the CSAT3 therefore the suggested correction was not used.

2.2.6.2 Data filtering

Results for F_{CH4} were filtered to omit the first and last half hour of each campaign due to pressure stabilization within the RMT-200's measurement cavity upon switching to and from external pump mode during instrument "initialization" and "power down" periods. Determinations of *NEE* were filtered to remove periods where condensation, rain, and particles intercepted the sensor path of the LI-7500 based on the instrument's diagnostic report. Diagnostic automatic gain control (AGC) values indicated when the LI-7500 was working properly (values between 50.00 and 56.25%), and when the sensor path was obstructed (<50.00%, >56.25%). All *NEE* values coinciding with non-optimal AGC values were removed. Both F_{CH4} and *NEE* were filtered to remove half-hour periods at night (PAR < 10 μmol m^{-2} s^{-1}) when the friction velocity (u*) was below a threshold of 0.15 m s^{-1} ($u*_{threshold}$). Malfunctions with the LI-7500 resulted in large gaps in the *NEE* data, making it difficult to distinguish the $u*_{threshold}$ with our dataset. Therefore, the $u*_{threshold}$ used in this study was determined from *NEE* data collected at the site in 2008 using a similar EC flux system at the site; 0.05 m s^{-1} u*-bin-averaged data from DOY 157 – 268 of 2008 (n = 616) where PAR < 10 μmol m^{-2} s^{-1}[*Swystun*, pers. comm.].

Flux determinations were removed when field staff occupied the 4.5 m scaffold for system maintenance and site photographs resulting in compromising the reliability in determinations using the CSAT3 and LI-7500. Erroneous F_{CH4} and *NEE* determinations were also removed when the gas power generator was running upwind (135 – 225°) of the

LI-7500 and intake tube. Error analysis as standard error for half-hourly F_{CH4} and *NEE* values over individual campaign periods was performed using the program SigmaPlot (Version 2000, Systat Software, Inc., San Jose, CA) to illustrate the variability within individual campaigns.

2.2.6.3 Gap-filling of Tair

There were occasions when the HMP45C at 3.9 m malfunctioned. Gaps in the data time series were filled using the relationship of Tair at 3.9 m to Tair at 1.8 m. Further gaps in the data time series were filled using the relationships of Tair at 3.9 m to a TC shielded from direct sunlight under the analyzer/control house roof, or for the Churchill Airport (Environment Canada) (Fig. A1). Gap-filled Tair (at 3.9 m) was then used to calculate cumulative growing degree days (ΣGDD) with a 0°C baseline temperature (T_b) as follows (4):

$$\sum GDD = \sum(Tmean - T_b) \tag{4}$$

where *Tmean* was the mean daily gap-filled temperature, in order to compare F_{CH4} for 2008 and 2009. Observing F_{CH4} in terms of ΣGDD heat units illustrates how influential temperature is as a driver of fluxes on a seasonal basis.

2.2.6.4 Relationships between F_{CH4} and *NEE* with temperature

Temperature-response curves using non-linear regression analysis were generated on 1°C bin-averaged F_{CH4} for all 2008 and 2009 data, as well as for spring of 2009 (DOY

150 – 200) using the program SigmaPlot. These flux-temperature relationships were then used to estimate F_{CH4} at Tair and Tsoil-0.05m of 5 and 15°C for determination of the temperature coefficient, Q_{10} [*Sommerkorn*, 2008] (4):

$$Q_{10} = \left(\frac{Fi}{Fo}\right)^{\left(\frac{10}{Ti-To}\right)} \quad (4)$$

where *Fo* and *To* are the reference flux and temperature, respectively, at 5°C, and *Fi* and *Ti* are new flux and temperature, respectively, at 15°C.

Half-hourly bin-averaged F_{CH4}, *NEE*, Tair and Tsoil-0.05m were plotted over a 24 h period for June 25, July 2 and 8, 2009 (DOY 176, 183, and 189), to observe diurnal temperature trends. The F_{CH4} –Tsoil-0.05m relationship for spring 2009 was also determined and used to empirically model F_{CH4} over the spring study period. Cumulative F_{CH4} (ΣF_{CH4}) for both measured and modelled data were then plotted with respect to half-hourly campaign periods, as well as continuously for the 2009 spring-melt period (DOY 150 – 200).

2.3 Results

2.3.1 Weather and environmental conditions

The 2008 and 2009 growing seasons (May – August) had contrasting weather conditions (Fig. 4). The 2008 season was slightly warmer in August and total rainfall was 90 mm lower for May – July compared to the long-term climate normal [*Environment Canada,* 2010] for the Churchill area (Table 1). In comparison, the 2009 growing season was very much cooler, by 3.3 – 5.6°C, for May – July, only slightly cooler in August, warmer in September, and had lower precipitation in May and August but higher precipitation in July than the climate normal (Table 1).

a) b)

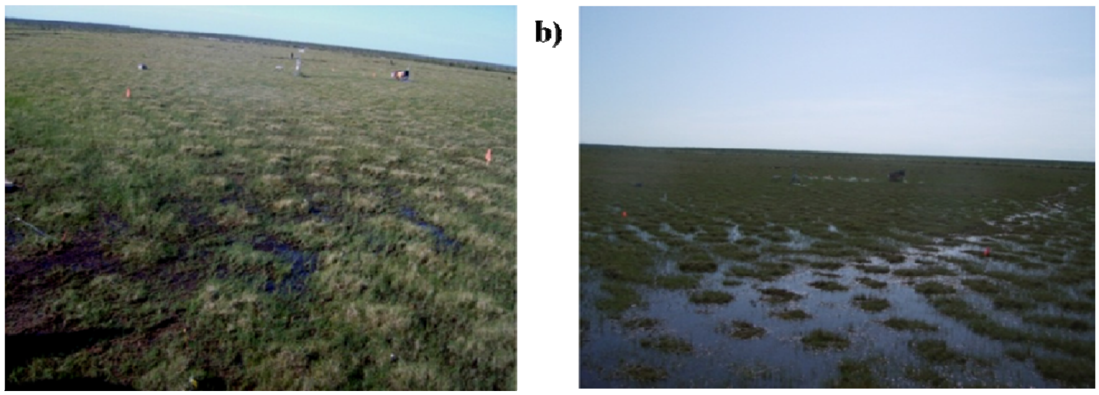


Figure 4: Contrasting mid-season conditions of the two field seasons at the fen (a) warm and dry; July 29, 2008 (DOY 211) (b) cool and wet; July 26, 2009 (DOY 207).

Table 1**:** Mean monthly air (Tair), soil at -0.05 m (Tsoil-0.05m) and soil at -0.60 m (Tsoil-0.60m) temperatures, and total monthly precipitation for the study site from May to October, 2008 and 2009. Also shown are the 1971-2000 climate normal for mean air temperature and total precipitation in the Churchill area#.

	May	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**May-Oct**
Mean Tair (°C)							
2008	-0.9	7.3	12.5	13.8	5.2	1.5	6.7
2009	-6.3	3.3	8.6	10.5	8.9	-0.3	4.1
Normal#	-0.7	6.6	12.0	11.7	5.6	-1.7	5.6
Precipitation (mm)							
2008	0.0	7	18	65	53	34	177
2009	0.0	40	85	26	---	---	---
Normal#	17.8	41	56	68	58	21	261
Mean Tsoil-0.05m (°C)							
2008	-2.0	7.3	12.3	12.6	5.8	2.0	6.3
2009	-1.7	1.9	9.7	11.2	---	---	---
Mean Tsoil-0.60m (°C)							
2008	-3.7	-0.9	-0.2	2.1	1.7	0.7	-0.05
2009	-1.6	-1.1	-0.5	1.4	---	---	---

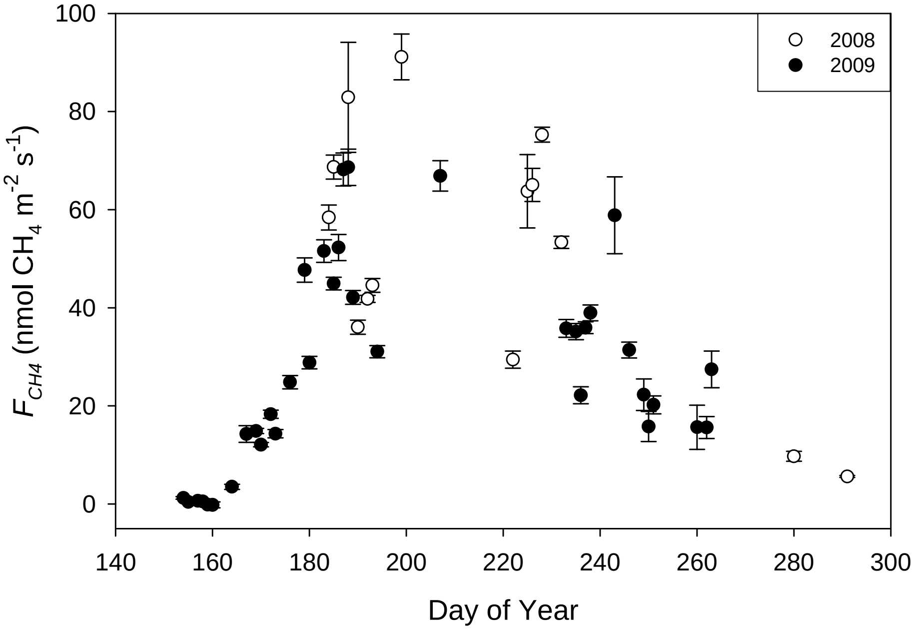
--- = loss of data due to animal intrusion of the weather station on August 26, 2009
= 1971 – 2000 climate normals for Churchill, Manitoba obtained from Environment Canada

Warmer air temperature resulted in greater soil warming at the 0.05 m depth for the months June and July in 2008 compared to the same months in 2009 (Table 1). At the 0.6 m depth in soil, mean monthly temperatures were similar for the study years with the exception of having been colder by 2.1°C in May 2008 than May 2009. The colder May temperature at 0.6 m soil depth in 2008 was due to mean monthly air temperatures for January through April in 2008 being several degrees lower than 2009 and winter precipitation leading to a 20 – 30 cm deeper snow pack in May 2009 than 2008 (data not shown). However, by August, mean soil temperature at 0.6 m was 0.7°C warmer in 2008 than 2009, likely because of the warmer 2008 summer air temperatures.

2.3.2 Growing season F_{CH4}

In both 2008 and 2009, F_{CH4} showed a notable seasonal trend, increasing in magnitude rapidly in the spring, reaching a peak between June 29 (DOY 180) and July 19 (DOY 200), and then gradually diminishing into the fall (Fig. 5a). In general, the 2008 measurement period had slightly higher F_{CH4} throughout the monitoring period than in 2009. Warmer temperatures as the growing season progressed produced greater positive F_{CH4} despite the lower water table position. This was because the water table was likely not yet a limiting factor for anaerobic conditions within the peat [*Christensen et al.*, 2003; *Long et al.*, 2009] being only 0.10 – 0.15 m from the peat surface of the sedge-lawn landscape unit. In 2008, F_{CH4} for individual campaigns ranged from 5.3 ± 0.20 to 91.1 ± 4.67 nmol CH_4 m^{-2} s^{-1} with a mean value of 50.6 ± 1.24 nmol CH_4 m^{-2} s^{-1} for all measurement campaigns, while 2009 values ranged from -0.12 ± 0.58 to 68.6 ± 3.7 nmol CH_4 m^{-2} s^{-1}, with a mean value of 27.9 ± 1.1 nmol CH_4 m^{-2} s^{-1}.

a)



b)

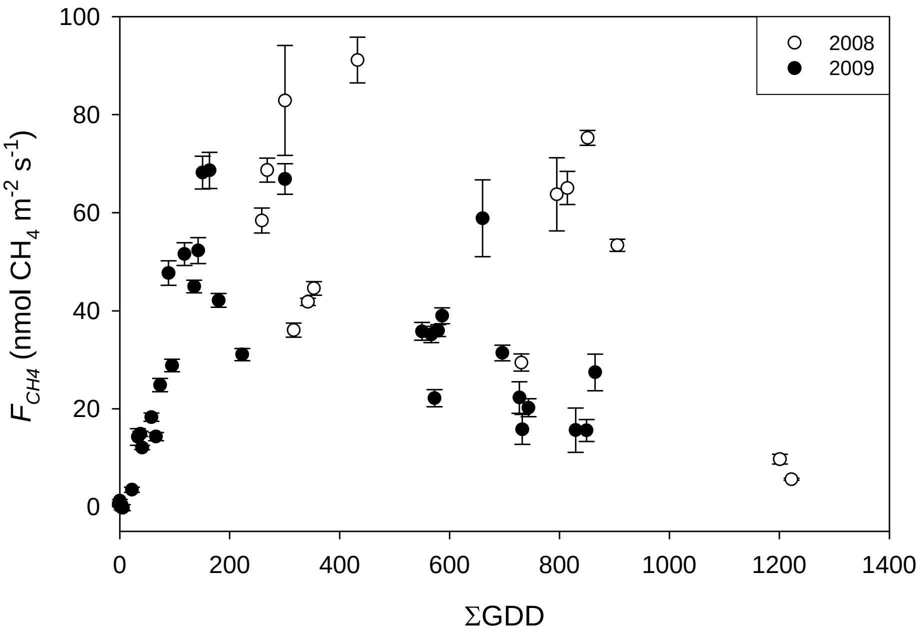


Figure 5: CH_4 flux (F_{CH4}) at the fen for 30-minute-averaged campaign periods (n=4-24: ± 1 SE shown) for (a) day of year, and (b) cumulative growing degree days (ΣGDD) in 2008 and 2009.

2.3.3 2009 spring-melt trends

The progression of melting of snow and ice at the site was categorized into three periods: Pre-melt, Melt, and Post-melt for spring-melt of 2009 (Fig. 6).The Pre-Melt period, May 30 – June 10, 2009 (DOY 150 – 161) had snow and ice cover (Fig. 7a). The Melt period, June 11 – June 21 (DOY 162 – 172), was the transitional period from snow and ice cover to open water at the fen (Fig. 7b and c, Fig. 8). In the Post-Melt period, June 22 – July 19 (DOY 173 – 200), all snow and ice cover at the fen had disappeared (Fig. 7d).

During the Pre-Melt period, F_{CH4} was near zero (-6 to 8 nmol CH_4 m^{-2} s^{-1}) as well as *NEE* (-1 to 1 μmol CO_2 m^{-2} s^{-1}) (Fig. 6). Air temperature remained mostly below 0°C until June 7 (DOY 158), and all soil depths remained below 0°C during this period (Fig. 6).

Throughout the Melt period, Tair remained mostly above 0°C, with daytime highs between 5 and 15°C (Fig. 6). All soil depths remained below 0°C until June 17 (DOY 168) when soil at the 5 cm depth thawed which warmed to a maximum of 10°C by the end of the period (Fig. 6). All other soil depths remained frozen (Fig. 6). A gradual increase in F_{CH4} from -7 to 26 nmol CH_4 m^{-2} s^{-1}, and *NEE* from -2 to 3 μmol CO_2 m^{-2} s^{-1} occurred during this period (Fig. 6).

In the Post-Melt period, F_{CH4} increased gradually with time, having a greater range in half-hourly averages of 7 to 95 nmol CH_4 m^{-2} s^{-1} (Fig. 6). The range of F_{CH4} was associated with a diurnal trend in emissions throughout the individual campaigns (Fig. 6). Diurnal trends were also evident in *NEE* (Fig. 6). Air temperature remained above 0°C throughout the period and daytime highs gradually increased from 10 to 23°C (Fig. 6).

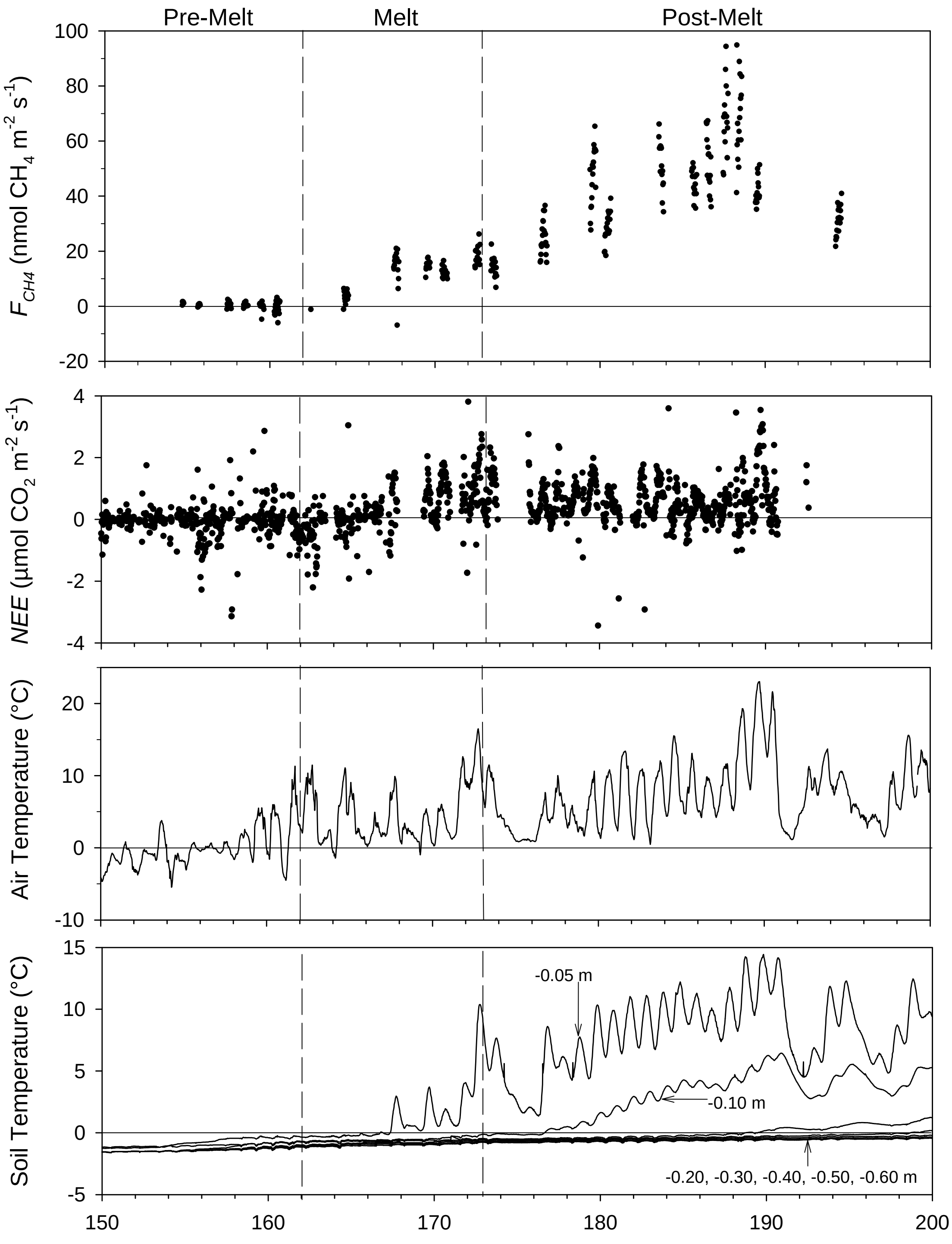


Figure 6: Spring period CH_4 flux (F_{CH4}), net ecosystem exchange of CO_2 (*NEE*), air temperature and soil temperatures for the fen from May 30 – July 19, 2009 (DOY 150-200).

Soil temperature at 5 cm depth reached a maximum of 14°C by the end of the Post-Melt period (Fig. 6). All other soil depths had temperature below 0°C with the exception of soil at 10 cm depth which became thawed on June 26 (DOY 177) (Fig. 6). Diurnal variation was evident for Tair and all soil temperatures however the magnitude of the variation decreased with greater soil depth.

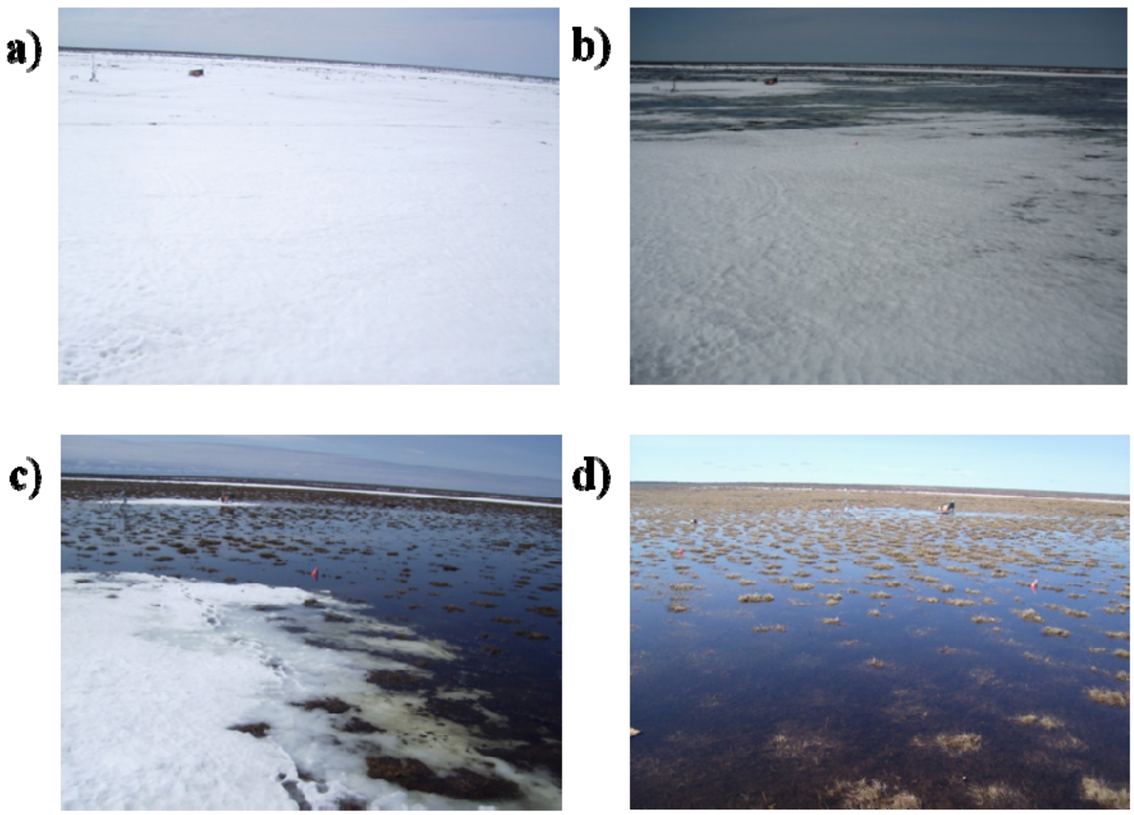


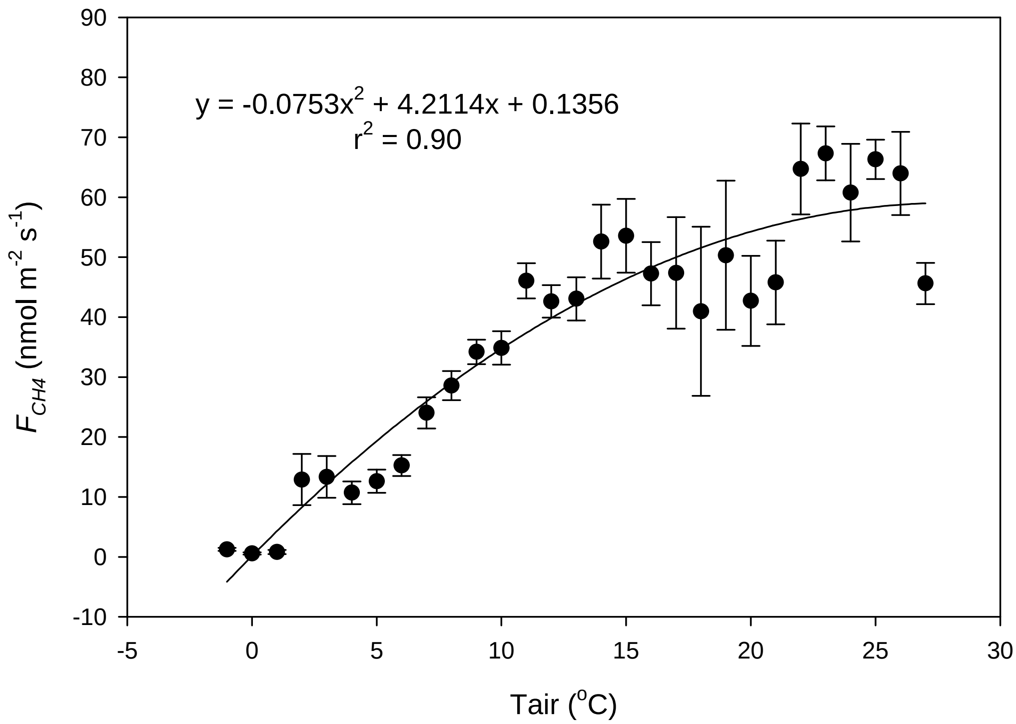
Figure 7: 2009 spring-melt conditions for the fen looking south-west of the flux station on (a) June 11 (DOY 162) (b) June 13 (DOY 164) (c) June 16 (DOY 167) (d) June 22 (DOY 173).

Figure 8: Melt conditions at the fen, west of the flux station, on June 13, 2009 (DOY 164) illustrating the snow melt water which inundated the smaller hummocks and the presence of ice within the hollows.

2.3.4 Temperature responses of F_{CH4}

Air and soil temperature were both associated with F_{CH4} during the 2008 and 2009 growing seasons (Fig. 9). Temperature-response curves showed high correlation of F_{CH4} with Tair ($r^2 = 0.90$) and Tsoil-0.05m ($r^2 = 0.93$) which resulted in Q_{10} values of 2.40 and 2.31 respectively (Fig. 9).

During the spring of 2009, diurnal fluctuations in air and soil temperatures lagged that of F_{CH4} and *NEE* (Fig. 10). It was observed that the timing of the peaks in both NEE and F_{CH4} were between 14:00 and 15:00, while the peak for Tair was at 18:00, and for Tsoil-0.05m was at 20:00 (Fig. 10). This indicates that although temperature influences NEE and F_{CH4}, other drivers are also to be considered.



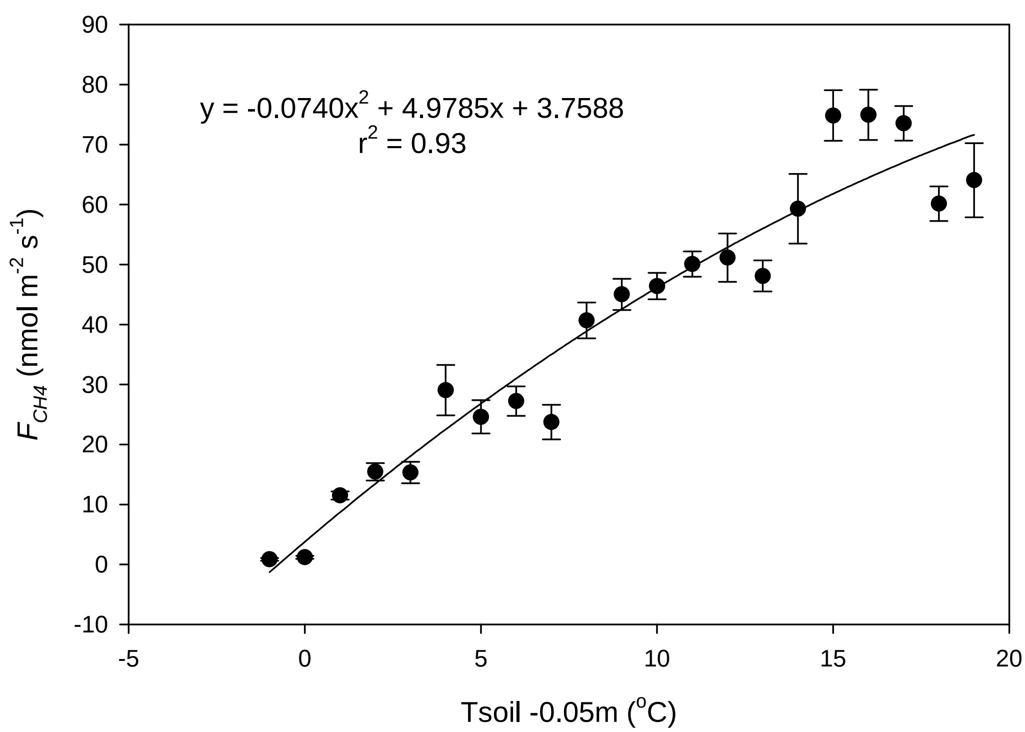


Figure 9: Bin-averaged (1°C) CH_4 flux (F_{CH4}) and ±1 SE for all measurement values in 2008 and 2009 in response to (a) air temperature at 3.9 m (Tair) (n = 3 – 83) and (b) soil temperature at 0.05 m depth (Tsoil-0.05m) (n = 5 – 85).

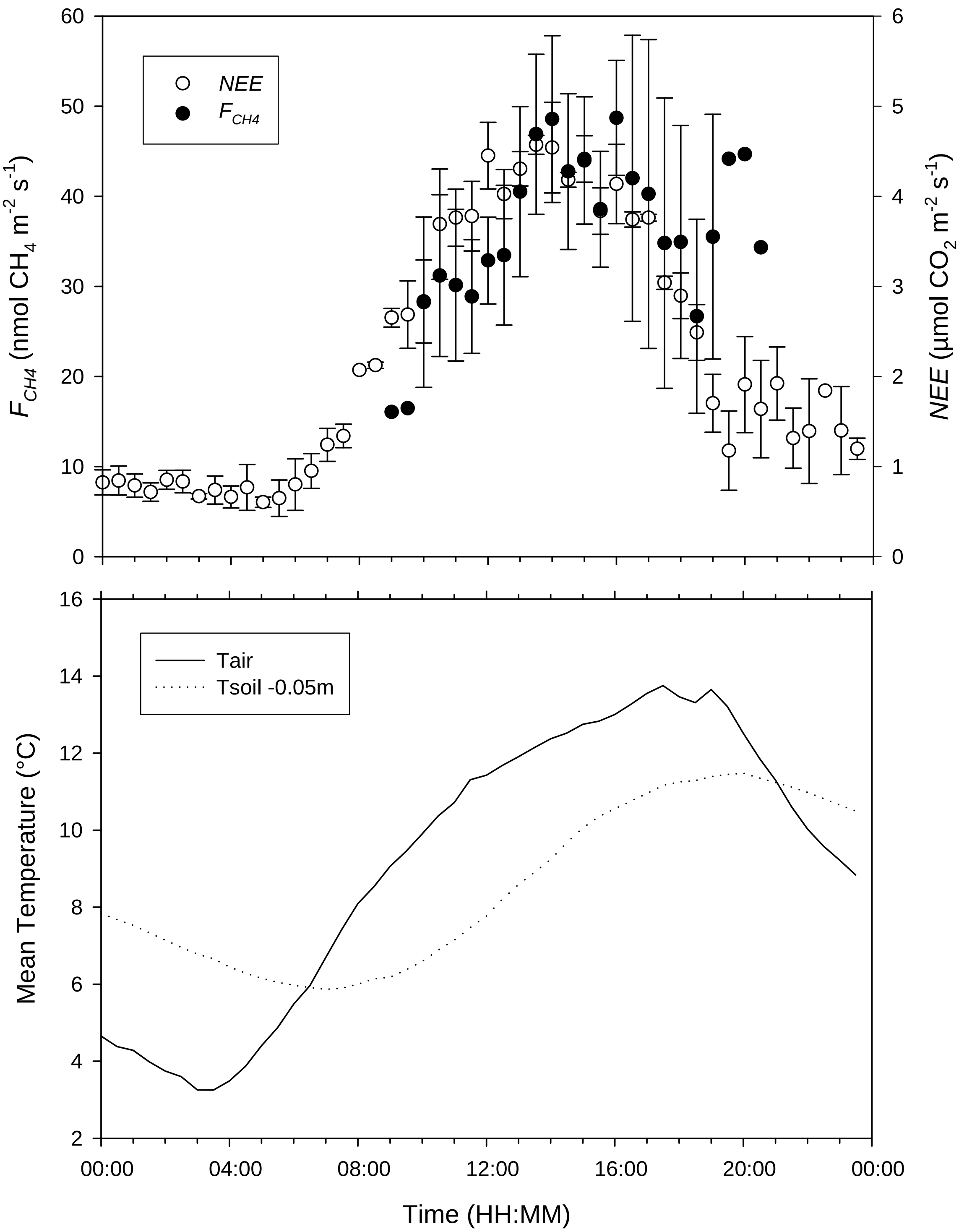


Figure 10: Diurnal trends in (a) mean half-hourly bin-averaged CH_4 flux (F_{CH4}) (n = 1 – 3) and net ecosystem exchange of CO_2 (*NEE*) (n = 3) (± 1 SE shown) and (b) air temperature at 3.9 m (Tair) and soil temperature at 0.05 m depth (Tsoil-0.05m) over day of year 176, 183, and 189 in 2009.

There was also less association of F_{CH4} with Tsoil-0.05m during the spring 2009 period (r^2 = 0.89). The temperature coefficient, Q_{10}, of 2.08 was lower during the spring period of 2009 (DOY 150 – 200) than for all of 2008 and 2009 (Fig. 11).

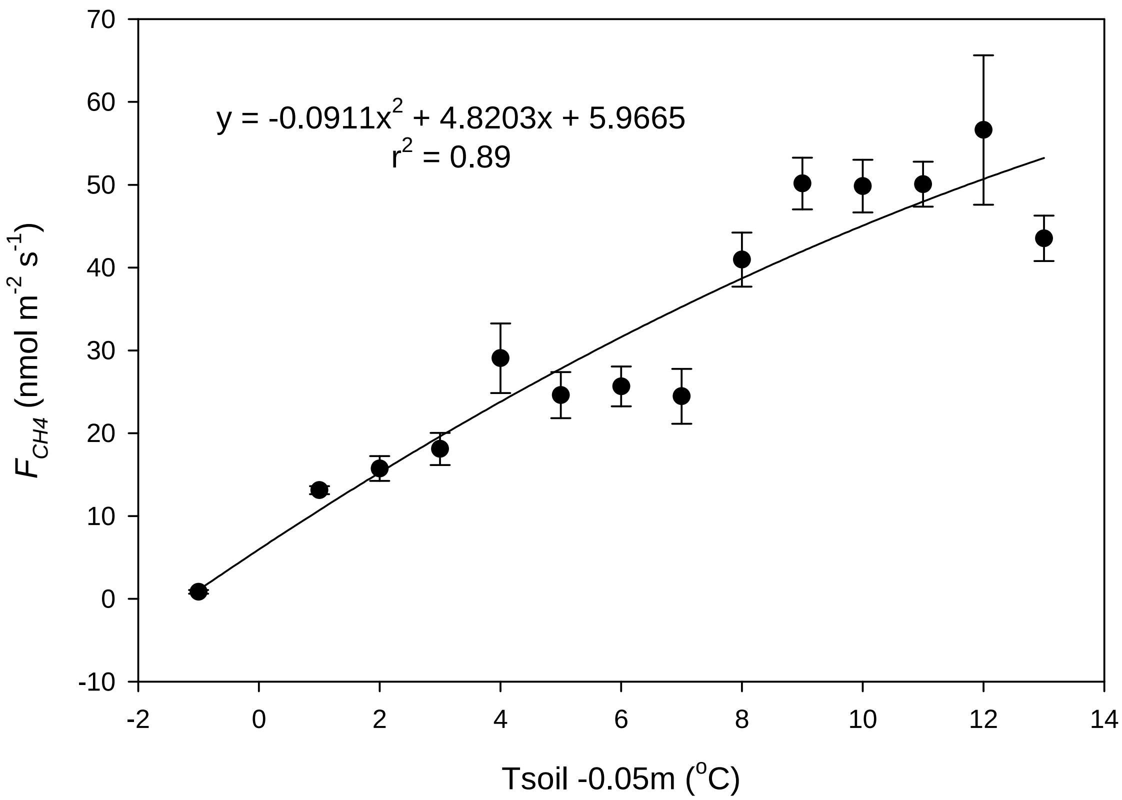


Figure 11: Bin-averaged (1°C) CH_4 flux (F_{CH4}) and ± 1 SE shown for the spring period of May 30 – July 19, 2009 (DOY 150 – 200) in response to soil temperature at 0.05m depth (Tsoil-0.05m) (n = 3 – 85).

Modelled half-hourly values for F_{CH4} over the spring of 2009 were similar to measured values (Fig. 12a). At the end of the measurement period, the measured ΣF_{CH4} was 8.62 μmol CH_4 m^{-2} or 95% of the modelled ΣF_{CH4} of 9.05 μmol CH_4 m^{-2}. Modelled

ΣF_{CH4} for the entire spring-melt period (DOY 150 – 200), including non-campaign periods indicated that the fen emitted 56.15 µmol CH_4 m^{-2} (Fig. 12b).

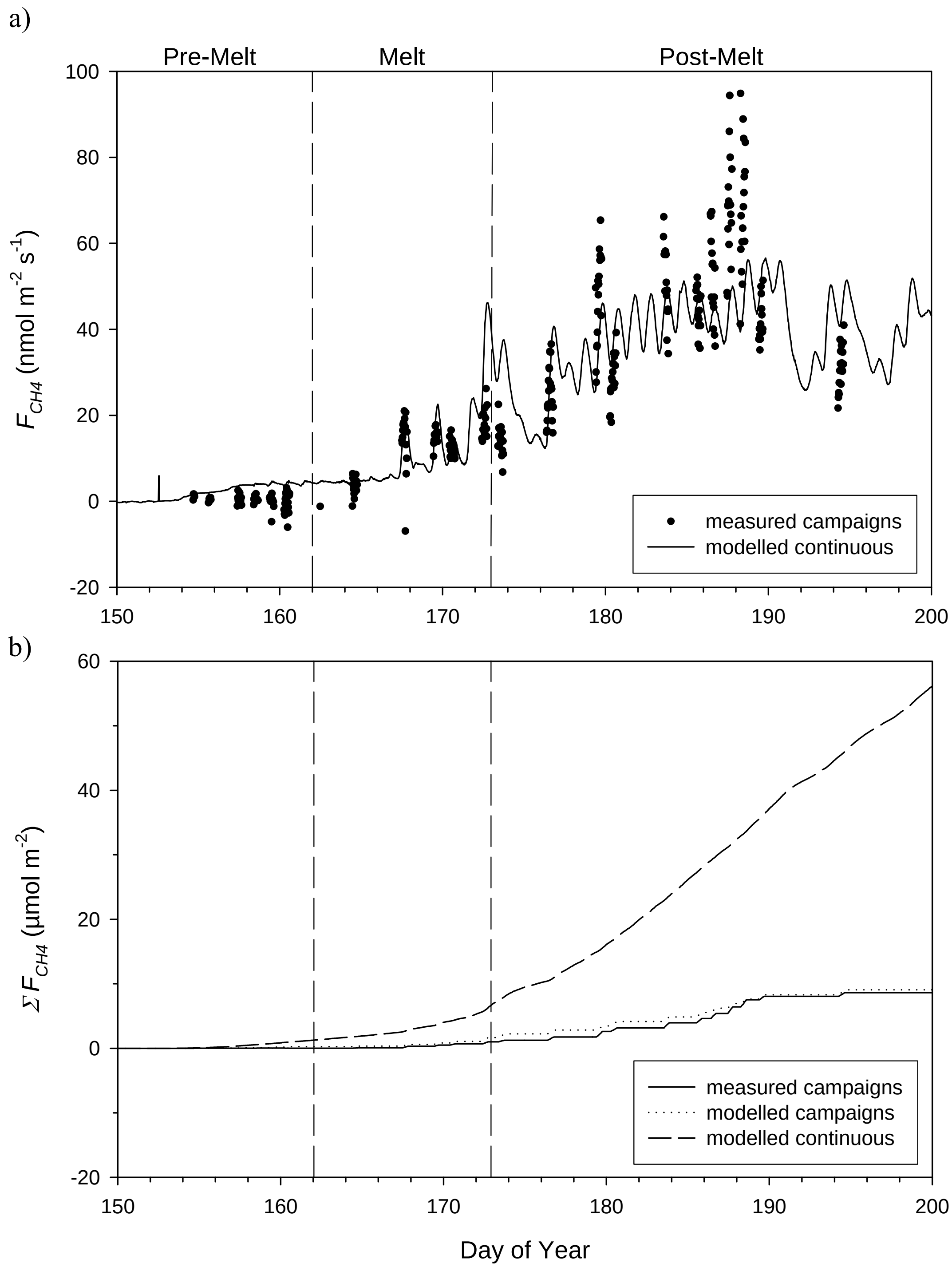


Figure 12: Measured half-hourly campaigns and modelled half-hourly (a) CH_4 flux (F_{CH4}) and (b) cumulative CH_4 flux (ΣF_{CH4}) for May 30 – July 19, 2009 (DOY 150-200). Modelled fluxes were derived from the temperature-response curve in Fig. 11.

2.4 Discussion

2.4.1 Seasonal trends in F_{CH4} for two contrasting field seasons

Very few studies in northern peatlands have measured F_{CH4} while incorporating off-axis ICOS. For a two week period in June of 2006, F_{CH4} measurements were obtained by the EC technique with the DLT-100 Fast Methane Analyzer (Los Gatos Research, Inc.) at a eutrophic peat meadow in the Netherlands, and showed a range of F_{CH4} from 0 to 80 nmol CH_4 m^{-2} s^{-1}, with a mean F_{CH4} of 30 nmol CH_4 m^{-2} s^{-1} [*Hendriks et al.*, 2008]. A DLT-100 Fast Methane Analyzer was also incorporated into an EC system over a wet sedge polygonal tundra site near Barrow, Alaska underlain by Histels (Histosol – USDA; Turbic Organic Cryosol – CSSC) which gave a mean F_{CH4} of 18 nmol CH_4 m^{-2} s^{-1} for June and July of 2007 [*Zona et al.*, 2009]. More recently, in 2008-2009, the new Fast Greenhouse Gas Analyzer from Los Gatos Research, Inc. was used with chambers to determine F_{CH4} from a hummock and hollow bog in Wales, and values ranged from 0 – 101 nmol CH_4 m^{-2} s^{-1} [*Baird et al.*, 2010]. These values are in line with F_{CH4} values obtained in this study. Measurements of ecosystem scale F_{CH4} using off-axis ICOS in combination with the EC method in northern Canadian peatlands has been achieved for the first time during this study.

Ecosystem scale measurements of F_{CH4} in northern peatlands using tunable diode laser spectroscopy with the EC method have shown similar results to our measurements. Determinations of F_{CH4} from a mesotrophic flark fen in Finland for the period of mid-August to mid-September, 1995 were 14 to 28 nmol CH_4 m^{-2} s^{-1} [*Heikkinen et al.*, 2002], and from September 29 – October 18, 1998 were between 0 to 34 nmol CH_4 m^{-2} s^{-1} [*Hargreaves et al.*, 2001], which are fluxes comparable to our study. A boreal oligotrophic open fen in Finland had F_{CH4} values ranging from -0.35 to 307 nmol CH_4 m^{-2} s^{-1} from May 2004 to February 2006 [*Riutta et al.*, 2007], and from -35 to 156 nmol CH_4 m^{-2} s^{-1} from March 2005 to February 2006 [*Rinne et al.*, 2007]. Low centred ice wedge polygons in the Lena River Delta were also studied using this technique, and showed F_{CH4} ranging between -35 to 104 nmol CH_4 m^{-2} s^{-1} over two field seasons, July 19 – October 22, 2003 and June 1 – July 21, 2004 [*Wille et al.*, 2008]. A boreal minerotrophic treed fen in Athabasca, Alberta was studied from May 24 – September 26, 2007 and had F_{CH4} values of -5 to 80 nmol CH_4 m^{-2} s^{-1} [*Long et al.*, 2009].

Previous studies at the same fen used in this study employed chambers to measure F_{CH4} and showed variability between years. From June 15 – August 30, 1989, F_{CH4} was determined to be -1.5 to 3.6 nmol CH_4 m^{-2} s^{-1}, while from June 15 – September 15, 1990 F_{CH4} values ranged from 0.72 to 17.7 nmol CH_4 m^{-2} s^{-1} respectively [*Rouse et al.*, 1995]. From May 24 – August 25, 2006 the mean F_{CH4} determined for the sedge-lawn landscape unit of the fen was 32 nmol CH_4 m^{-2} s^{-1}[*Churchill*, 2007]. Micrometeorological techniques have not been used to measure ecosystem F_{CH4} for the fen. *Rouse et al.*, [1995] weighted chamber F_{CH4} measurements based on the spatial extent of different landscape units. *Churchill* [2007] focused her study on F_{CH4} measurements for individual landscape units on independent sampling days, as well as on a seasonal basis. Therefore, the measurements obtained in this study are novel, an advance in integrating fluxes over the fen landscape, and of great importance for understanding ecosystem scale F_{CH4} from spring-melt to fall freeze-up at this site.

2.4.2 F_{CH4} response to spring-melt conditions

A F_{CH4} burst was not observed at the fen for the spring 2009 snow melt period, rather a gradual increase in F_{CH4} with increasing soil temperature. The lack of a burst was surprising considering we have observed gas bubbles to be trapped under fresh thin ice layers in the fall when overnight air temperatures drop below 0°C, as well as within thick winter ice at the fen. Gas bubbles in the ice of shallow lakes in the Churchill area have also been reported [*Duguay et al.*, 2002].

Observations have been made by others of F_{CH4} bursts during the spring-melt period in northern peatlands due to release of gas from bubbles trapped in ice [*Tokida et al.*, 2007] and within the anaerobic zone of soil [*Hargreaves et al.*, 2001]. *Tokida et al*. [2007] used chambers to measure spring-melt emissions for an ombrotrophic peatland in Japan from April 13 – 20, 2006. It was observed that emissions were near zero prior to ice melt between April 13 – 16, followed on April 17 by an emission burst of 439 nmol CH_4 m^{-2} s^{-1} over a one hour measurement period for plot A dominated by *Sphagnum* spp. and *Moliniopsis japonica*, and a simultaneous burst of 113 nmol CH_4 m^{-2} s^{-1} for plot B dominated by *Sphagnum* spp. and *Carex* spp. On April 18, plot A exhibited another CH_4 emission burst of 104 nmol CH_4 m^{-2} s^{-1} over a one hour measurement period, and plot B had a one-hour emission burst of 26 nmol CH_4 m^{-2} s^{-1}. These bursts were followed by F_{CH4} values from 0 to 17 nmol CH_4 m^{-2} s^{-1} for April 19 – 20 [*Tokida et al.*, 2007]. The ombrotrophic peatland, however, was not underlain by permafrost, and air temperatures throughout the winter and spring-melt period hovered around 0°C, indicating freeze-thaw cycles and waterlogged conditions underneath the snowpack throughout the measurement period [*Tokida et al.*, 2007]. Continuous spring period ecosystem scale F_{CH4}

measurements, obtained by the EC method using tunable diode laser spectroscopy for a mesotrophic flark fen in Finland dominated by *Carex* spp. and *Eriophorum angustifolium*, from May 23 – June 20, 1997, reported a maximum burst of 75 nmol CH_4 m^{-2} s^{-1}over a six hour period, while all other measurements were within the range of 12 to 50 nmol CH_4 m^{-2} s^{-1}. The F_{CH4} observed were highly variable throughout the month-long spring measurement period [*Hargreaves et al.*, 2001]. No permafrost was present at the Finnish fen, and the soil was thawed > 40 cm throughout the measurement period. However, the fen did have 15 – 20 cm of ice in hollows overlain by 30 cm of snow. *Wille et al.* [2008] also used the EC method with tuneable diode laser spectroscopy to capture F_{CH4} for wet low-centred polygonal tundra in the Lena River Delta, Siberia from early June (pre-melt) to mid-July (post-melt), 2004. During melt, F_{CH4} was highly variable with bursts around 5 – 6 mg m^{-2} h^{-1} (87 – 104 nmol CH_4 m^{-2} s^{-1}) that lasted 1 – 4 h, and then fluxes stabilized between -34 and 34 nmol CH_4 m^{-2} s^{-1} after the melt [*Wille et al.*, 2008]. The region was within the zone of continuous permafrost, and polygon centres were water saturated organic rich Typic Historthels (Gleyi-Histic Cryosol – International WRB; Gleysolic Organic Cryosol – CSSC) [*Wille et al.*, 2008].

In contrast, *Mastepanov et al.* [2008] showed similar results to our dataset for a graminoid fen underlain by continuous permafrost at Zackenberg Valley, north-east Greenland, measured with automated chambers and the Fast Methane Analyzer (Los Gatos Research Inc.). Spring melt CH_4 emissions were minimal and gradually increased from 0 – 2 mg CH_4 m^{-2} h^{-1} (0 – 35 nmol CH_4 m^{-2} s^{-1}) from July 1 – 21, 2006, and no emission burst was observed [*Mastepanov et al*., 2008]. However, a large burst of $F_{CH4,}$

extending from late September – mid-October, 2007, was measured with values of 12 – 18 mg CH_4 m^{-2} h^{-1} (208 – 313 nmol CH_4 m^{-2} s^{-1}) [*Mastepanov et al.*, 2008].

It is possible that the fen at Churchill, MB behaved similarly to the graminoid fen at Zackenberg Valley, having released large quantities of CH_4 to the atmosphere during the fall freeze-up period. The gradual increase in F_{CH4} in the spring likely indicates new production of CH_4 as the soil thawed and not over-winter stored CH_4 that was released from bubbles in the ice.

2.4.3 Contributions of soil depth to F_{CH4}

Temperature plays an integral role in the magnitude of F_{CH4} for northern peatlands, and affects F_{CH4} seasonally and diurnally [*Kim et al.*, 2007; *Hendriks et al.*, 2008; *Long et al.*, 2009]. At the fen, F_{CH4} was in part driven by soil temperature at 5 cm depth, both seasonally and during the spring-melt of 2009. Previous studies have selected soil temperatures at greater depths: 0 – 10 cm [*Verville et al.*, 1998; *Hargreaves et al.*, 2001], and 20 cm [*Wille et al.*, 2008] in permafrost zones, and 35 cm [*Rinne et al.*, 2007], and 50 cm [*Long et al.*, 2009] in zones with discontinuous or no permafrost, to be most influential as shown through temperature-response curves. These soil temperature depths could correspond with anaerobic zones that have the highest CH_4 production. In contrast, studies that performed temperature-response curves for daily *NEE* tended to have the best relationships with air temperature [*Aurela et al.*, 2007; *Golovatskaya and Dyukarev*, 2009; *Cai et al.*, 2010]. Night-time ecosystem respiration (*ER*), was controlled more by soil surface temperature [*Schreader et al.*, 1998; *Waddington et al.*, 1998; *Bubier, et al.*, 2002], and 2 to 5 cm depth soil temperature [*Hendriks et al.*, 2007] in boreal and

Subarctic peatlands with discontinuous or no permafrost, and from 0 to 5 cm depth for Arctic peatlands within the continuous permafrost zone [*Corradi et al.*, 2005; *Sommerkorn*, 2008]. These soil depths correspond with the typical aerobic zones of northern peatlands.

The Q_{10} values determined for the fen were within range of values associated with peatlands underlain by continuous permafrost. *Petrescu et al.* [2008] assigned Q_{10} values of 2-3 for the Kytalyk site in Siberia comprised of low centred ice-wedge polygons underlain by continuous permafrost, and a Q_{10} value of 4 for the Stordalen hummock and hollow mire in Sweden underlain by discontinuous permafrost [*Petrescu et al.*, 2008] based on Q_{10} values obtained from laboratory tests and modelling [*Walter and Heimann*, 2000]. The Q_{10} assignment made by *Petrescu, et al.* [2008] illustrates that Q_{10} values for F_{CH4} will be lower for soils underlain by continuous permafrost than those with discontinuous or no permafrost.

The temperature response of F_{CH4} from this study was greater than for CO_2 in northern terrestrial environments found in the literature. Values for Q_{10} ranged from 1.55 to 2.04 for *ER* in a treed fen in northern Alberta [*Cai et al.*, 2010], from 1.3 to 1.6 for *ER* at the Subarctic fen at Churchill, Manitoba [*Griffis et al.*, 2000] and from 1.8 to 2.0 for daily *NEE* for a poor fen and an extreme rich fen in northern Alberta [*Glenn et al.*, 2006].

Although Tair and Tsoil-0.05m were influential to *NEE* and F_{CH4}, peaks in both Tair and Tsoil-0.05m lagged peaks in *NEE* and F_{CH4} indicating that they were not the primary drivers behind diurnal variation in these fluxes during the spring-melt of 2009. During this time of the year most of the vegetation was brown, indicating that stomatal conductance via the *Carex* plants based on photosynthetic photon flux density (PPFD)

[*Mikkela et al.,*1995; *Garnet et al.,* 2005] would have been negligible. Increased consumption of CH_4 after midday when the soil was warmest is also not a possibility because both F_{CH4} and *NEE* declined in the afternoon, where NEE should have increased if consumption of CH_4 were to have occurred. A suggested driver would be surface soil temperature ($Tsoil_{surf}$). Net radiation would cause the surface of the soil to heat up faster than Tair. If $Tsoil_{surf}$ were to peak at the same time as F_{CH4} and *NEE* then it is likely to be one of the main drivers for these fluxes during the spring.

Modelling F_{CH4} using soil temperature at 5 cm depth over the 2009 spring-melt proved to match measured values quite well. Many C flux studies performed in northern peatlands have incorporated empirical non-linear regression relationships of fluxes and soil temperature for gap-filling CO_2 fluxes [*Glenn et al.*, 2006; *Humphreys et al.*, 2006; *Laine et al.*, 2006; *Aurela et al.*, 2007; *Lafleur and Humphreys*, 2007; *Roulet et al.*, 2007; *Sommerkorn*, 2008; *Golovatskaya and Dyukarev*, 2009; *Cai et al.*, 2010], as well as F_{CH4} [*Hargreaves et al.*, 2001; *Rinne et al.*, 2007; *Petrescu et al.*, 2008; *Wille et al.*, 2008; *Zona et al.*, 2009]. Based on our model we have been able to determine that the fen was a source of 56 µmol CH_4 m^{-2} during the spring-melt period of 2009 which, due to the global warming potential of CH_4, equates to 1.4 mmol m^{-2} as CO_2 equivalent emission.

2.5 Conclusions

It was observed that the EC flux measurement system integrating off-axis ICOS provided seasonal F_{CH4} values of approximately 0 to 90 nmol CH_4 m^{-2} s^{-1}, similar to previous studies which used EC while incorporating tunable diode laser spectroscopy or off-axis ICOS for ecosystem scale F_{CH4} measurements in northern peatlands. When observing the results of the two field seasons, warm and dry in 2008 compared to cool and wet in 2009, it was noted that warm temperatures produced greater positive F_{CH4}, despite the lower water table position. A melt-period CH_4 emission burst was not observed in 2009; rather a gradual increase in emission over the spring period was driven by increasing soil temperature at the 5 cm depth. There was a net emission of CO_2 over the spring period because of a lack of photosynthesis. Modelled F_{CH4} over the spring-melt period of 2009 using the temperature-response curve relationship with Tsoil-0.05m proved to match measured values quite well. Model-estimated F_{CH4} over the entire spring-melt period (DOY 150 – 200) showed the fen to be a net source of 1.4 mmol m^{-2} as CO_2 equivalent emission.

Very few studies have used the EC technique to study F_{CH4} in northern peatlands, and even fewer have incorporated off-axis ICOS. This study is novel in its determinations of ecosystem scale F_{CH4} while incorporating off-axis ICOS in EC measurements for northern peatlands in Canada. Further studies, with continuous data collection of F_{CH4} from the pre-melt period to the post-freeze-up period, need to occur in the future at the fen in Churchill, MB, as well as other northern peatland sites. Filling this information gap in the annual F_{CH4} cycle of northern peatlands is of the utmost importance for determining the contribution of CH_4 to the overall C and GHG budgets, so as to help better predict how northern peatlands will be affected climate change.

2.6 References

ACIA, 2004. Impacts of a warming Arctic: Arctic climate impact assessment. Cambridge University Press, Cambridge, UK. 1042 p.

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J.P., Vesala, T., Tuittila, E.S., Rinne, J., Haapanala, S. and Laine, J., 2007. CO_2 exchange of a sedge fen in southern Finland - the impact of a drought period. Tellus Series B-Chemical and Physical Meteorology, 59: 862-837.

Baer, D.S., Paul, J.B., Gupta, M. and O'Keefe, A., 2002. Sensitive absorption measurements in the near-infrared region using off-axis integrated-cavity-output spectroscopy. Applied Physics B: Laser and Optics, 75: 261-265.

Baird, A.J., Stamp, I., Heppell, C.M. and Green, S.M., 2010. CH_4 flux from peatlands: a new measurement method. Ecohydrology, doi: 10.1002/eco.109.

Baldocchi, D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology, 9: 479-492.

Barlett, K.B. and Harriss, R.C., 1993. Review and assessment of methane emissions from wetlands. Chemosphere, 26: 261-320.

Brown, R.J.E., 1970. Permafrost in Canada; its influence on Northern development. Canadian Building series, 4. University of Toronto Press [Toronto], vii, 234 p.

Bubier, J.L., Crill, P. and Mosedale, A., 2002. Net ecosystem CO_2 exchange measured by autochambers during the snow-cover season at a temperate peatland. Hydrological Processes, 16: 3667-3682.

Bubier, J.L. and Moore, T.R., 1994. An ecological perspective on methane emissions from northern wetlands. Trends in Ecology & Evolution, 9: 460-464.

Burba, G., McDermitt, D., Grelle, A., Anderson, D. and Xu, L., 2008. Addressing the influence of instrument surface heat exchange on the measurement of CO_2 flux from open-path gas analyzers. Global Change Biology, 14: 1854-1876.

Cai, T., Flanagan, L.B. and Syed, K.H., 2010. Warmer and drier conditions stimulate respiration more than photosynthesis in a boreal peatland ecosystem: analysis of automatic chambers and eddy covariance measurements. Plant, Cell and Environment, 33: 394-407.

Christensen, T.R., Ekberg, A., Strom, L., Mastepanov, M., Panikov, N., Oquist, M., Svensson, B.H., Nykanen, H., Martikainen, P.J. and Oskarsson, H., 2003. Factors controlling large scale variations in methane emissions from wetlands. Geophysical Research Letters, 30: 1414.

Christensen, T.R., Prentice, I.C., Kaplan, J., Haxeltine, A. and Sitch, S., 1996. Methane flux from northern wetlands and tundra – an ecosystem source modelling approach. Tellus Series B – Chemical and Physical Meteorology, 48: 652-661.

Churchill, J.A., 2007. Spatial variation of soil methane and nitrous oxide emissions in Subarctic environments of Churchill, Manitoba, University of Manitoba, Winnipeg, MB, Canada. 156 p., http://mspace.lib.umanitoba.ca/bitstream/1993/2453/1/Thesis.pdf

Corradi, C., Kolle, O., Walter, K., Zimov, S.A. and Schulze, E.D., 2005. Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. Global Change Biology, 11: 1910-1925.

Denmead, O.T., 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. Plant Soil, 309: 5-24.

Duguay, C.R., Pultz, T.J., Lafleur, P.M. and Drai, D., 2002. RADARSAT backscatter characteristics of ice growing on shallow sub-Arctic lakes, Churchill, Manitoba, Canada. Hydrological Processes, 16: 1631-1644.

Dunfield, P., Knowles, R., Dumont, R. and Moore, T.R., 1993. Methane production and consumption in temperate and Subarctic peat soils: response to temperature and pH. Soil Biology & Biogeochemistry, 25: 321-326.

Environment Canada, 2010. Canadian Climate Normals 1971-2000 – Churchill A. http://www.climate.weatheroffice.gc.ca/climate_normals/. Accessed March 8, 2010.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R., 2007. Changes in Atmospheric Constituents and in Radiative Forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 129 – 234.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C. and Zeng, N., 2006. Climate-carbon cycle feedback analysis: results from the (CMIP)-M-4 model intercomparison. Journal of Climate, 19: 3337-3353.

Garnet, K.N., Megonigal, J.P., Litchfield, C. and Taylor, G.E. Jr., 2005. Physiological control of leaf methane emission from wetland plants. Aquatic botany, 81: 141-155.

Glenn, A.J., Flanagan, L.B., Syed, K.H. and Carlson, P.J., 2006. Comparison of net ecosystem CO_2 exchange in two peatlands in western Canada with contrasting dominant vegetation, *Sphagnum* and *Carex*. Agricultural and Forest Meteorology, 140: 115-135.

Golovatskaya, E.A. and Dyukarev, E.A., 2009. Carbon budget of oligotrophic mire sites in the southern taiga of western Siberia. Plant Soil, 315: 19-34.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. Ecological Applications, 1: 182-195.

Griffis, T.J., Rouse, W.R. and Waddington, J.M., 2000. Scaling net ecosystem CO_2 exchange from the community to landscape-level at a Subarctic fen. Global Change Biology, 6: 459-473.

Grondahl, L., Friborg, T., Christensen, T.R., Ekberg, A., Elberling, B., Illeris, L., Nordstrom, C., Rennermalm, A., Sigsgaard, C. and Sogaard, H., 2008. Spatial and inter-annual variability of trace gas fluxes in a heterogeneous high-Arctic landscape. Advances in Ecological Research, 40: 473-498.

Hargreaves, K.J., Fowler, D., Pitcairn, C.E.R. and Aurela, M., 2001. Annual methane emission from Finnish mires estimated from eddy covariance campaign measurements. Theoretical and Applied Climatology, 70: 203-213.

Heikkinen, J.E.P., Maljanen, M., Aurela, M., Hargreaves, K.J. and Martikainen, P.J., 2002. Carbon dioxide and methane dynamics in a sub-arctic peatland in northern Finland. Polar Research, 21: 49-62

Hendriks, D.M.D., Dolman, A.J., van der Molen, M.K. and van Huissteden, J., 2008. A compact and stable eddy covariance set-up for methane measurements using off-axis integrated output spectroscopy. Atmospheric Chemistry and Physics, 8: 431-443.

Hendriks, D.M.D., van Huissteden, J., Dolman, A.J. and van der Molen, M.K., 2007. The full greenhouse gas balance of an abandoned peat meadow. Biogeosciences, 4: 411-424.

Humphreys, E.R., Lafleur, P.M., Flanagan, L.B., Hedstrom, N., Syed, K.H., Glenn, A.J. and Granger, R., 2006. Summer carbon dioxide and water vapour fluxes across a range of northern peatlands. Journal of Geophysical Research, 111, G04011, doi:10.1029/2005JG000111.

Kershaw, G.P. and McCulloch, J., 2007. Midwinter snowpack variation across the Arctic treeline, Churchill, Manitoba, Canada. Arctic, Antarctic and Alpine Research, 39: 9-15.

Kim, Y., Ueyama, M., Nakagawa, F., Tsunogai, U., Harazono, Y., and Tanaka, N., 2007. Assessment of winter fluxes of CO_2 and CH_4 in boreal forest soils of central Alaska estimated by the profile method and the chamber method: a diagnosis of methane emission and implications for the regional carbon budget. Tellus Series B – Chemical and Physical Meteorology, 59: 223-233.

Kolb, S., 2009. Aerobic methanol-oxidizing bacteria in soil. Fems Microbiology Letters, 300: 1-10.

Lafleur, P.M. and Humphreys, E.R., 2007. Spring warming and carbon dioxide exchange over low Arctic tundra in central Canada. Global Change Biology, 14: 740-756.

Lai, D.Y.F., 2009. Methane dynamics in northern peatlands: a review. Pedosphere, 19: 409-421.

Laine, A., Sottocornola, M., Kiely, G., Byrne, K.A., Wilson, D. and Tuittila, E.S., 2006. Estimating net ecosystem exchange in a patterned ecosystem: example from blanket bog. Agricultural and Forest Meteorology, 138: 231-243.

Limpens, J., Berendse, F., Blodau, C., Canadell. J.G., Freeman. C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G., 2008. Peatlands and the carbon cycle: from local processes to global implications. Biogeosciences, 5: 1475-1491.

Long, K.D., Flanagan, L.B. and Cai, T., 2009. Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. Global Change Biology, doi: 10.111/j.1365-2486.2009.02083.x.

Los Gatos Research, 2009. Methane Analyzers: Fast – Low Power – High Precision. http://www.lgrinc.com/documents/Methane-Analyzers-web.pdf. Accessed March 25, 2010.

Mastepanov, M., Sigsgaard, C., Dlugokencky, E.J., Houweling, S., Strom, L., Tamstorf, M.P. and Christensen, T.R., 2008. Large tundra methane burst during onset of freezing. Nature, 456: 628-630.

McGuire, A.D., Anderson, L.G., Christensen, T.R., Dallimore, S., Guo, L., Hayes, D.J., Heimann, M., Lorenson, T.D., Macdonald, R.W. and Roulet, N., 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs, 79: 523-555.

Mikkela, C., Sundh, I., Svensson, B.H. and Nilsson, M., 1995. Diurnal variation in methane emission in relation to the water table, soil temperature, climate and vegetation cover in a Swedish acid mire. Biogeochemistry, 28: 93-114.

Moore, T.R. and Dalva, M., 1997. Methane and carbon dioxide exchange potentials of peat soils in aerobic and anaerobic laboratory incubations. Soil Biology & Biochemistry, 29: 1157-1164.

Moore, T.R., Roulet, N.T. and Waddington, J.M., 1998. Uncertainty in predicting the effect of climate change on the carbon cycling of Canadian peatlands. Climatic Change, 40: 229-245.

NWWG, 1997. The Canadian Wetland Classification System: Second Edition, Wetland Research Centre, University of Waterloo, ON, Canada. 68 p.

Petrescu, A.M.R., van Huissteden, J., Jackowicz-Korczynski, M., Yurova, A., Christensen, T.R., Crill, P.M., Backstrand, K. and Maximov, T.C., 2008. Modelling CH_4 emissions from Arctic wetlands: effects of hydrological parameterization. Biogeosciences, 5: 111-121.

Raddatz, R.L., Papakyriakou, T.N., Swystun, K.A. and Tenuta, M., 2009. Evapotranspiration from a wetland tundra sedge fen: surface resistance of peat for land-surface schemes. Agricultural and Forest Meteorology, 149: 851-861.

Reddy, K.M. and DeLaune, R.D., 2008. Ch 16: Wetlands and Global Climate Change, In: Biogeochemistry of Wetlands: Science and Applications. CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, pp. 599-621.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.P., Tuittila, E.S. and Vesala, T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus Series B – Chemical and Physical Meteorology, 59: 449-457.

Riutta, T., Laine, J., Aurela, M., Rinne, J., Vesala, T., Laurila, T., Haapanala, S., Pihlatie, M. and Tuittila, E.S., 2007. Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem. Tellus Series B – Chemical and Physical Meteorology, 59: 838-852.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. and Bubier, J., 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology, 13: 397-411.

Rouse, W.R., Bello, R.L., D'Souza, A., Griffis, T.J. and Lafleur, P.M., 2002. The annual carbon budget for fen and forest in a wetland at Arctic treeline. Arctic, 55: 229-237.

Rouse, W.R., Holland, S. and Moore, T.R., 1995. Variability in methane emissions from wetlands at northern treeline near Churchill, Manitoba, Canada. Arctic and Alpine Research, 27: 146-156.

Schimel, J.P., 1995. Plant transport and methane production as controls on methane flux from Arctic wet meadow. Biogeochemistry, 28: 183-200.

Schreader, C.P., Rouse, W.R., Griffis, T.J., Boudreau, L.D. and Blanken, P.D., 1998. Carbon dioxide fluxes in a northern fen during a hot, dry summer. Global Biogeochemical Cycles, 12: 729-740.

Scott, G.A.J., 1995. Canada's vegetation: a world perspective. McGill-Queen's University Press, Montreal and Kingston, 361 p.

Sommerkorn, M., 2008. Micro-topographical patterns unravel controls of soil water and temperature on soil respiration in three Siberian tundra systems. Soil Biology and Biochemistry, 40: 1792-1802.

Suyker, A.E., Verma, S.B., Clement, R.J. and Billesbach, D.P., 1996. Methane flux in a boreal fen: season-long measurement by eddy correlation. Journal of Geophysical Research – Atmospheres, 101(D22): 28637-28647.

Svensson, B.H., Christensen, T.R., Johansson, E. and Oquist, M., 1999. Interdecadal changes in CO_2 and CH_4 fluxes of a Subarctic mire: Stordalen revisited after 20 years. Oikos, 85: 22-30.

Syed, K.H., Flanagan, L.B., Carlson, P.J., Glenn, A.J. and Van Gaalen, K.E., 2006. Environmental control of net ecosystem CO_2 exchange and carbon balance in a treed moderately rich fen in northern Alberta. Agricultural and Forest Meteorology, 140: 97-114.

Tanner, C.B. and Thurtell, G.W., 1969. Sensible heat flux measurements with a yaw sphere and thermometer: anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer. TR Ecom 66-G22-F, Department of Soil Science, University of Wisconsin, Madison, WI.

Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. Global and Planetary Change, 53: 222-232.

Tarnocai, C., Ping, C.L., and Kimble, J., 2007. Carbon Cycles in the Permafrost Region of North America. In King, A.W., Dilling, L., Zimmerman, G.P., Fairman, D.M., Houghton, R.A., Marland, G., Rose, A.Z., and Wilbanks, T.J. (Editors). The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, Chapter 12, pp. 127-138.

Tokida, T., Mizoguchi, M., Miyazaki,T., Kagemoto, A., Nagata, O. and Hatano, R., 2007. Episodic release of methane bubbles from peatland during spring thaw. Chemosphere, 70: 165-171.

Turetsky, M.R., Wieder, R.K. and Vitt, D.H., 2002. Boreal peatland C fluxes under varying permafrost regimes. Soil Biology & Biogeochemistry, 34: 904-912.

Updegraff, K., Bridgham, S.D., Pastor, J., Weishampel, P. and Harth, C., 2001. Response of CO_2 and CH_4 emissions from peatlands to warming and water table manipulations. Ecological Applications, 11: 311-326.

Verville, J.H., Hobbie, S.E., Chapin, F.S. and Hooper, D.U., 1998. Response of tundra CH_4 and CO_2 flux to manipulation of temperature and vegetation. Biogeochemistry, 41: 215-235.

Waddington, J.M., Griffis, T.J. and Rouse, W.R., 1998. Northern Canadian wetlands: net ecosystem CO_2 exchange and climatic change. Climate Change, 40: 267-275.

Walter, B.P. and Heimann, M., 2000. A process-based, climate-sensitive model to derive methane emissions from natural wetlands: application to five wetland sites, sensitivity to model parameters, and climate. Global Biogeochemical Cycles, 14: 745-765.

Webb, E.K., Pearman, G. and Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society, 106: 85-100.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D. and Pfeiffer, E.M., 2008. Methane emission from Siberian Arctic polygonal tundra: eddy covariance measurements and modeling. Global Change Biology, 14: 1395-1408.

Yu, K.W. and Patrick, W.H., 2004. Redox window with minimum global warming potential contribution from rice soils. Soil Science Society of America Journal, 68: 2086-2091.

Zona, D., Oechel, W.C., Kochendorfer, J., Paw U, K.T., Salyuk, A.N., Olivas, P.C., Oberbauer, S.F. and Lipson, D.A., 2009. Methane fluxes during the initiation of a large-scale water table manipulation experiment in the Alaskan Arctic tundra. Global Biogeochemical Cycles, 23, GB2013, doi:10.1029/2009GB003487.

3. SYNTHESIS

3.1 Significance

Northern peatlands are extensive within Canada, covering 1.1x10^6 km^2 [*Tarnocai*, 2006] and store 112 Pg carbon (C) within peatlands underlain by permafrost [*Tarnocai et al.*, 2007]. Therefore, it is important to study C flux dynamics in northern peatlands at present to provide baseline data for climate models in order to accurately predict how changes in temperature and precipitation will affect C fluxes from these ecosystems in the future. At the Subarctic fen at Churchill, Manitoba, an off grid eddy covariance (EC) system was developed to study both net ecosystem exchange of carbon dioxide (*NEE*) and methane fluxes (F_{CH4}); the first of its kind in Arctic and Subarctic peatlands of Canada. The system was successful at collecting baseline data for ecosystem scale F_{CH4} at the fen based on measurement campaigns as well as nearly continuous measurements of *NEE* from June 29 – October 18, 2008 and May 30 – September 20, 2009.

Measurements made by the EC system were able to capture the ecosystem scale F_{CH4} over the 2008 and 2009 growing seasons which had contrasting temperature and precipitation patterns. The EC system was also able to provide the first ecosystem scale measurements of F_{CH4} during a spring-melt period (May 30 – July 19, 2009) at the fen, and for a Subarctic peatland in Canada; the data with which my thesis has been focussed. During the spring-melt of 2009, EC measurements also provided a general understanding of *NEE* for the fen.

The thesis objectives were successfully met. It was observed that F_{CH4} was greater over the 2008 than 2009 field season due to warmer air temperatures, despite having a lower water table. During the spring melt period of 2009, the fen remained in a state of positive NEE, indicative of net respiration and a lack of green-up and photosynthesis in the plants. A gradual increase in F_{CH4} with increase in soil temperature was found to have occurred during the spring-melt of 2009 with no burst in emissions due to CH_4 trapped in winter ice. This result has led us to question if the CH_4 emission burst was occurring in the fall during soil freeze-up. Soil temperature at 5 cm depth (Tsoil-0.05m) was found to be influential on F_{CH4}, and the Tsoil-0.05m – F_{CH4} relationship was used for modeling F_{CH4} over the entire spring melt period of 2009. The cumulative F_{CH4} for the spring melt of 2009 was found to be 1.4 mmol m^{-2} as CO_2 equivalent emission (based on modeled F_{CH4}) making F_{CH4} an important contributor to GHG emissions during this season.

Climate change could have a considerable effect on the C flux budget at the fen. Increased air and soil temperatures could begin to melt the continuous permafrost at the fen, thus the fen would become wetter over the short term, increasing F_{CH4}, making it a bigger source of C. However, once the permafrost becomes sporadic or absent, increased air temperature might increase evapotranspiration which will allow the fen water level to decline and thus soil will become more aerobic. More aerobic soil and increased soil temperatures could lead to increased decomposition and soil respiration while decreasing F_{CH4}. These conditions could also lead to greater shrub encroachment and more plant communities which prefer drier soil conditions thus allowing for greater uptake of carbon dioxide by plants, increasing the C sink capacity.

3.2 Improvements

Suggested improvements to the methodology would be to have incorporated longer campaign periods, and to have performed more 24 hour F_{CH4} campaigns during spring melt, growing season, and fall freeze-up in order to capture diurnal variation in F_{CH4}. Incorporation of the two smaller pumps into the closed-path methane EC system over both the 2008 and 2009 field seasons would have reduced the power requirements of the off-grid system. Additionally, better use of solar and wind power could have resulted in less dependence on the gas generator which introduces additional hydrocarbons into the air in the vicinity of the EC measurement instruments. Automating the EC system with use of radio or infrared telemetry or via satellite communication would also have been helpful in reducing the number of site visitations, as well as aiding in observation of real-time data and assisting with the diagnosis of technical issues from either or both the Churchill Northern Studies Centre and the Department of Soil Science at the University of Manitoba. Finally, the establishment of a boardwalk from Twin Lakes Road to the flux station and met station would have been of value for preserving the integrity of the fen, as regular visitation has created disturbed vegetation along pathways to both stations. This breakdown of sedge and moss could affect both soil respiration and F_{CH4}.

Investigation of the energy balance could have been beneficial, particularly for understanding how latent heat flux correlates with *NEE* and F_{CH4}. Latent heat flux would tell us about evapotranspiration at the fen, and indirectly how dry the fen would be and whether the plants were under moisture stress, all of which would affect *NEE* and F_{CH4}. Footprint analysis would have also been of value for understanding the dominant wind directions over the fen to know if Twin Lakes Road and other infrastructure at the site were within the footprint and influencing C fluxes. Footprint analysis would also have helped in positioning the EC measurement instruments better so that we were sure that they were positioned to capture fluxes from the dominant wind directions with the least amount of obstruction which could influence wind eddies from upwind. The use of silicone gas profilers in the soil and snowpack could have also been useful for understanding the movement of CH_4 and CO_2 within these media during the spring-melt period. Sampling the gas composition of bubbles trapped within the winter ice at the fen would have been valuable to know as the trapped gases would affect fluxes which occur during spring-melt. Examination of the relationship of water level height with F_{CH4} could have improved upon our understanding of the drivers of F_{CH4} at the fen. Finally, there is a need to determine a baseline for the amount of C stored within the peat as well as the imports and exports of soluble C for the fen at present in order to monitor and predict changes to the fen ecosystem over time and under varying climate change scenarios.

3.3 Future work

The 2010 field season at the fen will improve on measurements which have been collected over the past two years. Data collection for 2010 commenced on May 6 in order to capture the pre-melt C fluxes and will continue until the end of October to capture the post-freeze-up period. The addition of an external gas reservoir has made it possible to extend the F_{CH4} campaign periods to greater than 24 hours, and allow for more regular diurnal measurement campaigns.

Another exciting improvement to the EC flux system at the fen will be the introduction of the new LI-7700 Open-Path Methane Analyzer (LI-COR Biosci., Lincoln, NE). The LI-7700 has lower power requirements than the closed-path RMT-200 Fast Methane Analyzer (Los Gatos Research, Inc., Mountain View, CA) which requires the use of external pumps to run at the required 10 Hz data collection frequency. A comparative study of the F_{CH4} obtained from the open-path and closed-path systems will be undertaken.

Two areas of focus for the 2010 field season are diurnal trends in F_{CH4} throughout different seasons, i.e. spring, growing season, and fall, as well as to collect an extensive dataset of F_{CH4} during the fall freeze-up period to see if methane emission bursts occur at the fen during this time period. Other suggested studies for future consideration are to monitor stomatal conductance within the *Carex aquatilis* and *Eriophorum angustifolium* to see if F_{CH4} is affected by the opening and closing of stomata within these hydrophytes at the fen, as well as linking our C flux data to normalized digital vegetation indices (NDVI) technology which has the potential to model C fluxes using plant greening indices via remote sensing techniques from space.

It is our intention to incorporate our data into a 5 year C flux study at the Subarctic fen at Churchill, Manitoba. Short-term C flux studies run the risk of incorporating anomalous study periods which could lead to misrepresentation of the general C flux trends for the site. Therefore, monitoring C fluxes over longer time periods is important for understanding the inter-annual variability and general trends in C flux at the fen and allowing for more accurate modeling of C fluxes under varying climate change scenarios.

3.4 References

Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. Global and Planetary Change, 53: 222-232.

Tarnocai, C., Ping, C.L., and Kimble, J., 2007. Carbon Cycles in the Permafrost Region of North America, In King, A.W., Dilling, L., Zimmerman, G.P., Fairman, D.M., Houghton, R.A., Marland, G., Rose, A.Z., and Wilbanks, T.J. (Editors) - The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, National Oceanic and Atmospheric

Administration, National Climatic Data Center, Asheville, NC, USA, Chapter 12, pp. 127-138.

A. APPENDIX

A.1 Air Temperature Comparison

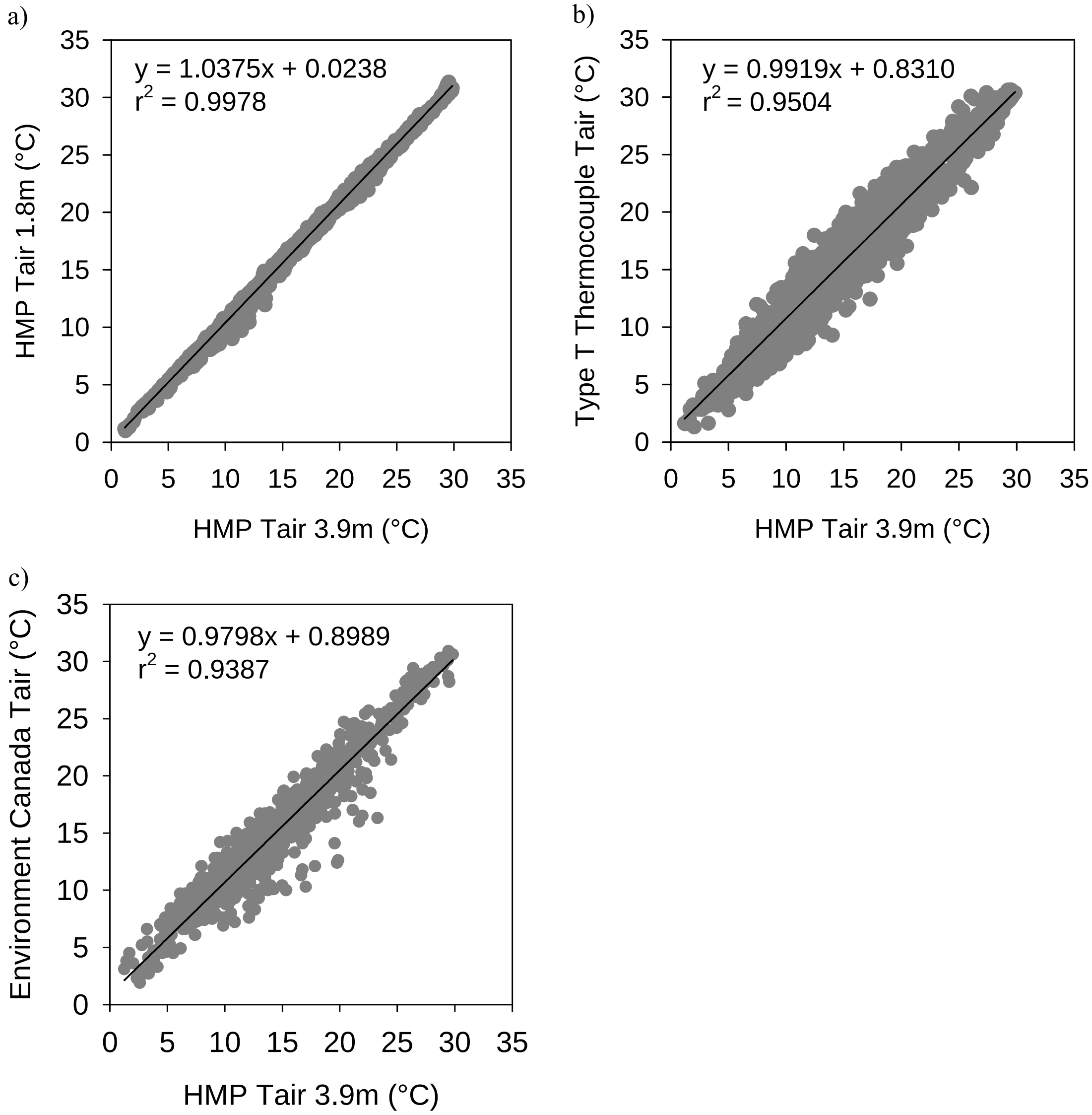


Figure A1: Comparison of Tair from the HMP-45C Temperature/Relative Humidity Probe at 3.9 m at the fen met station from July 9 – August 29 2009 (DOY 190 – 243) with (a) HMP-45C at 1.8 m at the fen met station (n = 2593), (b) Type T thermocouple at the fen flux station (n = 2105), and (c) Environment Canada's weather station at the Churchill Airport (n = 1248).