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Influence of Hudson Bay on the Carbon Dynamics of a Hudson Bay Lowlands Coastal Site

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Original Research

Abstract

Eddy Covariance (EC) estimates of Net Ecosystem Exchange (NEE) and the surface energy balance were gathered from an elevated peat plateau within the Hudson Bay Lowlands near Churchill, Manitoba, Canada (58° 43' 46"N, 93° 49' 57"W) during the growing season of 2007. Data were segregated into onshore and offshore wind regimes to assess the advective influence of the generally cold and moist Hudson Bay air masses compared to generally warm and dry air masses of non-marine origin. Monthly average net ecosystem exchange (NEE) ranged from an uptake of 0.2 $\mu\text{mol}/\text{m}^2/\text{s}$ in September to 5.6 $\mu\text{mol}/\text{m}^2/\text{s}$ in July. Over the growing season, onshore winds from Hudson Bay contributed to an average 4.2°C reduction in air temperature and an NEE increase of 27%. When normalized with respect to sunlight receipt, the ratio of gross primary production to photosynthetically active radiation (GPP/PAR) was 26% stronger for offshore regimes than for onshore, while the ratio of ecosystem respiration to PAR (ER/PAR) was 71% stronger for offshore regimes. It was concluded that GPP maintains the same strength for both wind regimes, while ER is significantly stronger for offshore regimes, resulting in reduced NEE capacity during periods when winds originate from inland.

Keywords: global warming, carbon dioxide, photosynthesis, respiration, Hudson Bay Lowlands, advection, eddy covariance, peatlands

Introduction

The carbon (C) balance of northern ecosystems plays an important role in observed and projected climate warming. Although the photosynthetic rates for peatlands are relatively low, the total amount of C stored in them is approximately 450×10^3 TgC, or about 30% of the global terrestrial C pool (Gorham 1991; Smith *et al.* 2004), as they represent strong C sinks in rich and slowly decomposing soils (Corradi *et al.* 2005). The Hudson Bay Lowlands, off the west coast of Hudson Bay, are the second largest continuous peatlands in the world, spanning 250,000 km² and comprising 25% of Canada's wetlands (Riley 2011). In the northern portion of the Hudson Bay Lowlands within the Province of Manitoba, peat thickness reaches 4 m, with an overall average depth of about 0.5 m (Dredge and Mott 2003). Accumulations over the past *ca.* 4500 years are generally greatest inland and diminish towards the coast which is still progressing seaward as new land emerges from Hudson Bay due to isostatic uplift. The strength of the C sink is a result of inhibited decomposition in anerobic and frozen soil conditions (Burton *et al.* 1996; Cai *et al.* 2010), and it has been accumulating at a long term average rate of 21 gC/m²/year (Clymo *et al.* 1998). However, projected climate warming, causing longer growing season, will likely affect northern ecosystems more strongly than in any other parts of the globe, with measurable consequences on the hydrological and carbon cycles (Cess *et al.* 1991; Rizzo and Wiken 1992; Chapman and Walsh 1993; Myneni *et al.* 1997; Serreze *et al.* 2000).

The amplification of the warming in the circumpolar north is primarily a result of positive feedback processes, most notably the surface-albedo/surface-temperature feedback, whereby increased air temperatures will result in the melting of snow and ice, which will further decrease the albedo, and enhance warming through greater absorption of solar radiation at the surface

(Cess *et al.* 1991; Chapin *et al.* 2005; Hinzman *et al.* 2005). Another important positive feedback effect is from a prolonged thawing of carbon-rich permafrost soils, which could release stored organic C through microbial respiration in the form of carbon dioxide (CO₂) and methane (CH₄), depending on the water table depth. The carbon released under increasing temperatures further increases the greenhouse effect by contributing to the atmospheric CO₂ concentration (Armentano and Menges 1986; Oechel *et al.* 1993; Zimov *et al.* 2006).

Although allowances are made within climate projection models for the interplay of feedback mechanisms, there still remain large uncertainties as to how some ecosystems will respond to a warming climate (Callaghan *et al.* 2004; Luo 2007; Heimann and Reichstein 2008), particularly in the north. Thus, it is important to quantify with field experiments the exchange of CO₂ between northern ecosystems and the atmosphere that will increase our understanding of their functioning under future warming scenarios. Characterizing the drivers of CO₂ exchange in Subarctic peatlands will establish the sensitivity of these active carbon sinks. In addition, warming temperatures have the potential to increase evaporation rates (Chapin *et al.* 2005) and dry out substantial areas of wetlands (Chivers *et al.* 2009). Peatlands are exceptionally vulnerable to drying out, as they have extremely large water contents when wet, and an equal amount of air content when dry (Rouse 2000), which suggests that a sink-source threshold of Net Ecosystem Exchange (NEE) is easy to cross. The sensitivity of these ecosystems is still uncertain, as some studies report that they are net sources of atmospheric CO₂ (Griffis *et al.* 2000; Rouse *et al.* 2002), while others report them as sinks (Tans *et al.* 1990; Griffis *et al.* 2000; Aurela *et al.* 2002; Roulet *et al.* 2007; Cai *et al.* 2010). What is likely is that productive, peat-accumulating wetlands have the potential to become large carbon sources under increasing air

temperatures, which will induce greater respiration (Armentano and Menges 1986; Oechel and Billings 1992; Zimov *et al.* 1999; Aurela *et al.* 2002; Dutta *et al.* 2006; Cai *et al.* 2010).

There have been a number of studies that have measured carbon fluxes in northern wetlands (Hamilton *et al.* 1994; Burton *et al.* 1996; Waddington and Roulet 1996; Griffis *et al.* 2000; Roulet *et al.* 2007), but the influence of Hudson Bay (via temperature and moisture) on these fluxes has not been investigated. Hudson Bay is a massive inland sea ($3.9 \times 10^9 \text{ km}^2$) which historically was completely free of ice only in September (Danielson 1971) but more recently has attained ice-free status in August (Gagnon and Gough 2005). It is responsible for extending southward the range of Arctic flora and fauna, the continental treeline and permafrost into central Canada. The current rate of disappearance of sea-ice is 11% per decade since 1968 (Henry 2011), resulting in an extension of the ice-free season that will impact significantly on the surrounding terrestrial environment. An energy balance study by Rouse and Bello (1985) concluded that there is a strong dependence of the energy balance of three different sites (1 km, 2 km and 65 km inland) within the Hudson Bay Lowlands on the advective wind direction around Hudson Bay. This has been confirmed by others (Lafleur and Rouse 1988; Rouse *et al.* 1997). The current study serves as an extension to these findings to fill an important gap in our understanding of the advective influence of Hudson Bay on terrestrial carbon dynamics. It is expected that Ecosystem Respiration (ER) will increase with warmer soil temperatures, associated with offshore wind regimes, but the response of Gross Primary Productivity (GPP) to the same influences requires further investigation. Offshore wind regimes during the growing season are associated with warmer and drier air masses of continental origin, while onshore wind regimes are associated with cooler and moister air masses originating off the Bay.

This study addresses the advective influence of Hudson Bay on the carbon dynamics of the Hudson Bay Lowlands at an elevated peat plateau near Churchill, Manitoba, Canada. The primary objectives are to (1) understand the environmental variables that influence the variability in NEE, GPP and ER of a Subarctic peat plateau during the growing season; (2) quantify the advective influence of Hudson Bay on the CO₂ dynamics of the coastal peatlands through onshore and offshore wind analysis; (3) and ensure that measurement bias due to vegetation heterogeneity is addressed in flux computations.

Draft

Methods

Study site description

Measurements for this study were collected between May 31, 2007 and September 18, 2007 as part of the ArcticNet Theme 3.2 campaign (ArcticNet 2015). The study was conducted at an elevated peat plateau, 20 km east of Churchill, Manitoba (58° 43' 46"N, 093° 49' 57"W) and approximately 5 km south of the Hudson Bay coastline (Fig. 1) that runs east-west locally. The length of the day on the summer solstice is approximately 18.5 hours. The measurement site was located 17.5 m above sea level, with the ground gently sloping down towards the shore (3.5 m/km). Based on the elevation, the mineral soils at the site emerged from Hudson Bay approximately 1600 years ago, based on a 0.01 m/year isostatic rebound rate (Stella *et al.* 2007). The climate is classified as *Low Arctic* (Rouse 1993) with cold winters and large summer-winter temperature contrasts. Mean annual temperature is -6.5°C, and mean total precipitation is 452 mm with about 40% arriving as snow. The lowest daily average temperatures occur in January (-26.0°C), and the highest daily average is in July (12.7°C) (Environment Canada, 1981-2010 climate normal). The peat layer is 1.5 m thick, while maximum active layer depths are 45 cm. The site is located approximately 80 km north of the continental treeline, with scattered trees such as *Larix laricina* (larch or tamarack) and *Picea glauca* (white spruce) present in low numbers locally with shrubs such as *Salix spp.* (willow) and *Betula glandulosa* (birch) common at greater distances from the tower. The peat plateau comprises high center ice-wedge polygons dominated by mosses (*Dicranium elongatum*, *Tomenthypnum nitens*, *Aulacomnium spp.*) and lichens (*Cladina spp.*) as well as *Ericaceae* notably *Rhododendron decumbens* (dwarf labrador tea), *Empetrum nigrum* (crowberry), *Vaccinium vitis-idaea* (low ground cranberry) and the herb

Rubus chamaemorus (cloudberry). High center polygon peatlands dominate the inaccessible interior portion of the Hudson Bay Lowlands, comprising approximately 12,000 km² in Northern Manitoba (Dredge and Nixon 1983; Bello and Smith 1990) but are highly underrepresented in the coastal zone. The peat plateau under study is approximately 6 ha in areal extent and within 2 km of the Churchill Northern Studies Centre on the Twin Lakes Rd., providing a unique opportunity to examine net ecosystem exchange from habitats of this nature.

Throughout the growing season, the coastal zone of Hudson Bay is subjected to abrupt changes in weather owing to passages of frontal systems, as well as the effect of sea-breeze which can lower temperatures by as much as 25°C in a half-hour, especially when the Bay is still ice covered. In attributing a certain portion of the measured ecosystem response to changes in the accompanying air mass characteristics alone, throughout the various phenological stages of plant growth, it was important to first assess the extent to which differences in plant cover between the onshore and offshore directions might contribute to the observed differences in NEE. A detailed plant survey was conducted radially along 16 compass directions from the measurement tower in 22.5-degree increments, by measuring plant cover using 50 cm x 50 cm quadrats at 2 m intervals along each 100 m long transect. Understory cover comprised the vascular species, lichen, moss, water, rock while the overstory groups comprised the shrubs coniferous trees and cloudberry (Table 1). Cloudberry was classified as overstory due to its late leafout and large and variable proportionate cover compared to other vascular species. The influence of plant cover groups on measured CO₂ fluxes for onshore and offshore regimes was assessed using a weighted footprint analysis after Schuepp *et al.* (1990). The results were statistically tested (Table 2) to ensure that the site asymmetry did not influence the differences in measured fluxes. Plant cover proportions to the north and south were statistically different, but by less than 4.5% in all cases, well within

the closure accuracy of the flux system, suggesting that the tower was optimally located for the purposes of this study.

Instrumentation

The micrometeorological method of eddy covariance (EC) was applied to measure the turbulent fluxes of CO₂, latent and sensible heat in the surface layer. It directly measures the scalar constituents and correlates those measurements to vertical wind velocity to give vertical fluxes. The system consisted of two fast-response instruments; three-dimensional wind components were measured by a sonic anemometer, model ATI-V style, (Applied Technologies, Inc.) logging the 20 Hz median of u,v,w wind components sampled at 200 Hz; the mean concentrations of CO₂ and H₂O were logged at 20 Hz using a non-dispersive open-path infrared gas analyzer (NDIR), model LI7500, (LI-COR Inc., Lincoln, NE, USA). Both instruments were mounted adjacent to each other separated by 12 cm, at a height of 1.49 m above the peat surface, while the LI7500 was mounted with a slight tilt. Data were logged to a datalogger (Campbell Scientific Inc., CR3000) using serial and SDM communications.

Slow-response ancillary data were collected to describe the meteorological conditions of the site every 30 minutes. A net radiometer (Middleton CN1) was placed on an adjacent tower at the same height as the fast-response instruments, which measured the net radiation surrounding the tower as Q^* (W/m²). A pyranometer (Eppley PSP) measured incoming solar radiation as R_g (W/m²); three soil heat flux plates (Middleton CN3) were placed at 2 cm below the surface as Q_G (W/m²). The slow-response instruments were connected to a Campbell Scientific CR23x data logger. PPFD (photosynthetic photon flux density) was acquired by applying a linear model to

the R_g data. The linear model was developed from the data collected at an EC station approximately 1 km away.

Data Processing

The high frequency flux data were processed with an open-source EC software, EddyPro 4.1.0 (LI-COR Biogeosciences, Lincoln, NE, USA). The eddy fluxes were calculated as the covariance between turbulent fluctuations in the vertical wind component and the scalar densities of CO_2 and H_2O using covariance optimization for time lag compensation. The data were averaged over 30 minutes, derived from Reynolds block averaging for trend removal. The sonic anemometer was adjusted for tilt using the planar fit method (Wilczak *et al.* 2001) by taking into account wind fields observed throughout the data collection period. High-pass filtering for low frequency data loss was performed using a block average detrend method after Moncrieff *et al.* (2004). A low-pass high frequency filter for data loss in the high frequency range was performed after Moncrieff *et al.* (1997), which accounts for the lateral and longitudinal sensor separation, sensor time response, scalar and vector path averaging (Foken *et al.* 2008). An off-season uptake correction has been performed to account for additional instrument-related sensible heat flux generation during temperatures below -10°C , following a method proposed by Burba *et al.* (2008). The fluxes were corrected for the effect of temperature and humidity fluctuations in trace gas concentrations that were not part of the investigated flux, using the WPL correction (Webb *et al.* 1980). Periods when less than 90% of the high frequency flux was available were marked as missing values and addressed during the post-processing. The resultant 30-minute CO_2 fluxes represent NEE, or the balance between the total flux that entered the ecosystem and the total flux that left the ecosystem.

Post Processing

The flux data were flagged using the 1-9 system after Foken (2004), which incorporates a steady-state, integral turbulence test, and horizontal advection tests. As advised, classes 7-9 have been removed from the dataset and marked as missing data, accounting for 6.9% of the total data. Data loss due to adverse weather and instrument malfunctioning accounted for 16% of the total data. Data loss due to data failing statistical analysis tests, performed after Vickers and Mahrt (1997), and after manual screening accounted for 7.3%. Of the remaining data, approximately 4.9% of the nighttime fluxes were removed using a u_* filter. For the removal of periods under non-turbulent conditions, the u_* filter was applied after Reichstein *et al.* (2005). The method involves the binning of temperature values to produce 6 temperature classes, which are further subdivided into 20 u_* classes. The u_* threshold value was determined to be 0.082 m/s. The total data loss added up to 35.1%, which was gap-filled. A random error of $\pm 0.12 \mu\text{mol/m}^2/\text{s}$ was estimated following Moncrieff *et al.* (1996).

Since the EC method is only able to measure NEE, it is necessary to partition it into the two component fluxes that make up the total exchange – ER and GPP. In order to obtain ER, we used one of the most common methods which employs nighttime respiration data as a function of air temperature and apply the same relationship to daytime values. Respiration has been modeled using an Arrhenius equation modified by Lloyd and Taylor (1994) as an exponential regression model derived from all available, non-gap-filled 30-min fluxes:

$$ER = ER_{ref} e^{\left[E_o \left(\frac{1}{T_{ref} - T_o} \right) - \left(\frac{1}{T - T_o} \right) \right]} \quad (1)$$

where ER_{ref} is the respiration rate at the reference temperature, T_{ref} , set to 10°C and T_o is the regression parameter kept constant at -46.02°C as in the original model. The activation energy parameter, E_o , was adjusted to achieve the most optimal model fit.

The gap-filling was done after Falge *et al.* (2001) and modified by Reichstein *et al.* (2005). Single 30-minute gaps were filled by linear interpolation (Falge *et al.* 2001); larger gaps were filled using mean diurnal variation with a 14-day window that looks for the flux under similar atmospheric conditions (global radiation (R_g , W/m²) air temperature (°C, T), vapour pressure deficit (kPa, VPD)) (Reichstein *et al.* 2005), which was the most consistent method based on 15 different methods analyzed by Moffat *et al.* (2007). The gaps in the energy fluxes were filled in the same manner.

Data Treatment

In order to better understand and quantify the effects of Hudson Bay on the Hudson Bay Lowlands, the flux data were differentiated between onshore and offshore wind regimes. The study site was situated on a nearly perpendicular tangent with respect to the Hudson Bay shoreline, which runs due east to west. For this reason, winds originating from north of the east-west tangent were considered to be onshore winds; winds originating from south of the east-west tangent were considered to be offshore winds. Due to the smaller frequency of onshore wind regimes taking place at night, the analysis concentrates on monthly averages using daytime

values, which are representative of both wind regimes. The monthly average is considered a long enough time period to gather data that are representative of both wind regimes.

In order to assess how well the EC system performed, the energy balance closure was considered, calculated as the ratio of $\frac{Q_H + Q_E}{Q^* - Q_G}$, where Q^* is net radiation, Q_H is the sensible heat flux, Q_E is the latent heat flux and Q_G is the ground heat flux, all in units of W/m^2 . On average, the system underestimated the turbulent fluxes, but there was a difference between onshore and offshore regimes. During onshore regimes, the closure was 87%, while under offshore regimes it was 64%. The difference may be due to larger amount of offshore regimes occurring during nighttime hours which commonly results in more stable atmospheric conditions. Other northern peatland studies have reported energy balance closure between 70% and 91% (Lafleur *et al.* 2001; Lafleur *et al.* 2003; Sottocornola and Kiely 2010; Runkle *et al.* 2014). The fluxes presented have been compensated to achieve energy balance closure.

Given that the dataset was post-processed to produce just two test groups – onshore and offshore – the statistical tests performed for this study were student's two-tailed t-tests assuming equal variances.

Results

Environmental Conditions

During the calendar year of 2007, the mean daily air temperature was -9.9°C , slightly cooler than the climate normal of -6.5°C (Table 3). During the study period, July experienced the highest mean temperature of 15.4°C , while September had the lowest mean temperature of 5.4°C . All normal monthly temperatures were within ± 1 standard deviation of the observed mean monthly temperatures, except for July, which was 2 standard deviations higher than the climate normal. The 2007 calendar year was drier than normal, with 338 mm of precipitation, compared to a 30-year average of 432 mm. The observed precipitation values were 48.2 (44.2), 30.2 (59.8), 44.4 (69.4) and 87.5 (69.9) mm for June, July August and September, respectively; bracketed numbers are climatological values. Thus, July and August were slightly drier and warmer than average.

The precipitation (P) and evaporation (E) patterns over the study period are shown in Fig. 2, during which evaporation exceeded precipitation for most of the season. For a nearly two-week period from DOY 160 to DOY 170, precipitation exceeded evaporation, associated with spring showers, but lower temperatures suppressed a strong evaporation response. The daily evaporation rates decreased over the season and were especially low into September when the evaporation rate decreases and the energy receipt was low. The total evaporation during the measurement period was 218 mm, while the total rainfall amounted to 193 mm, resulting in an

evaporative efficiency (E/P) of 1.12, indicating a net decline of ecosystem water storage and a receding water table.

Temperature Regimes

The differences in meteorological conditions between the two wind regimes were most pronounced for temperature (Fig. 3). The distinctive differences in diurnal behavior between on- and offshore regimes are noteworthy, as offshore air temperatures rose significantly during the daytime, while onshore temperatures exhibited much smaller maxima, owing to the large differences in surface sensible heat exchange between the tundra and Hudson Bay. In June, the onshore diurnal temperatures did not rise beyond 6°C, while the offshore temperatures hovered around 10°C during the daytime hours. Both regimes experienced a pronounced warming into July, where the daytime highs averaged 16°C for onshore and 23°C for offshore. Into August, both regimes cooled, with the offshore temperatures continuing to be warmer, while September temperatures showed patterns similar to June. Thus, the study was able to capture the diurnal temperature variation during the growing season that contributed to the significant plant activities of photosynthesis and respiration. On average for the season, offshore T was 4.15°C higher than onshore, highlighting the importance of the thermal depression created by Hudson Bay.

Energy Balance

Q^* appeared to be larger when winds were blowing offshore during the two coldest months, June and September, associated with the greatest onshore-offshore temperature contrast (Fig. 4). A reversed pattern is observed for July and August, where onshore regimes were associated with greater Q^* . Q_G showed stronger soil warming during offshore regimes in June and September, but a reversed role during July and August. Over the entire growing season, the ground experienced a net gain of 60 MJ/m^2 through surface exchange during onshore regimes, while 28 MJ/m^2 entered the ground during offshore regimes. Q_H was higher for onshore than offshore wind regimes, with a progressive decrease over the measurement period, rather than peaking during July when Q^* and T experienced their highest values. By the end of the season, onshore and offshore sensible heating amounted to 377 MJ/m^2 and 79 MJ/m^2 , respectively. Q_E was smaller during onshore regime for June and September. At the end of the measurement period, onshore and offshore Q_E amounted to 365 MJ/m^2 and 173 MJ/m^2 , respectively. The seasonal flux totals were strongly influenced by the higher frequency (56% larger) of onshore wind.

Table 4 shows normalized values of Q_H , Q_E , and Q_G with respect to Q^* by dividing each of them by Q^* . The ratios were derived from an average of all 30-minute daytime measurement periods occurring in the onshore or the offshore directions for a given month, from June through September. The partitioning of net radiation into evaporation does not show statistically significant onshore-offshore differences for any month although there was an apparent increase of 15% over the entire season existed while winds were blowing offshore. The proportion of net radiation used in warming the atmosphere, Q_H/Q^* , was consistently larger during onshore regimes. Lastly, the proportion of net radiation used in ground heating, Q_G/Q^* tended to be

stronger during offshore wind regimes on average for all months, particularly in July and August and 64% larger on average over the entire season.

Response of GPP, ER and NEE to Microclimate Variables

Daily average NEE during the four month period ranged from $-0.2 \mu\text{mol}/\text{m}^2/\text{s}$ in the middle of September (JD 261), to $-5.6 \mu\text{mol}/\text{m}^2/\text{s}$ towards the end of July (JD 207) (Fig. 5). The month of June experienced a relatively consistent net uptake of CO_2 of about $-1.5 \mu\text{mol}/\text{m}^2/\text{s}$, but started to increase (higher negative values) in early July (around DOY 170). However, the net uptake started to decrease in August and by the end of September, the NEE values started to approach zero. The ecosystem was a consistent net sink for CO_2 throughout the measurement period. On a monthly basis, the largest uptake occurred in July ($53.0 \text{ gC}/\text{m}^2$ or $4.4 \text{ mol}/\text{m}^2$), while the lowest uptake occurred in August ($25.5 \text{ gC}/\text{m}^2$ or $2.13 \text{ mol}/\text{m}^2$). Although GPP was larger in August ($113.9 \text{ gC}/\text{m}^2$ or $9.49 \text{ mol}/\text{m}^2$) than in June ($80.7 \text{ gC}/\text{m}^2$ or $6.73 \text{ mol}/\text{m}^2$), the ecosystem respiration was substantially higher in August ($88.4 \text{ gC}/\text{m}^2$ or $7.37 \mu\text{mol}/\text{m}^2$) than in June ($48.7 \text{ gC}/\text{m}^2$ or $4.06 \text{ mol}/\text{m}^2$).

The distinctiveness of ecosystem functioning under opposing wind regimes is shown in Table 5, as monthly means calculated from all 30-minute daytime measurements. Net ecosystem exchange was consistently larger under onshore regimes with statistically significant differences for all months except September, with the largest difference of 37% in July. Ecosystem respiration was always larger during offshore winds, ranging from 20% higher in August to 45% higher in June.

Monthly average GPP differences are less apparent over the summer, as GPP was higher during offshore regimes in June and September only. Over the entire measurement period, there is no statistically significant difference in GPP between onshore and offshore regimes. ER, GPP and NEE monthly averages do not account for potential biases created by the diurnal timing of onshore and offshore winds, particularly those that may occur as a result of the sea breeze effect. Thus, carbon fluxes have been normalized to photosynthetically active radiation ($\text{PAR} \times 100$), in Table 5, which reveals a stronger photosynthetic efficiency during offshore winds; up to 32% stronger in July.

Similarly, PAR-normalized ecosystem respiration was always stronger for offshore winds; up to 91% stronger in July. The interplay between GPP and ER, reflected in the ratio of the two, ER/GPP, describes how much of GPP is offset by ER. For all months and therefore the entire season, ER/GPP was always larger when winds were offshore, implying that a greater proportion of assimilation was returned to the atmosphere through respiration during offshore regimes. The ecosystem remained a net sink for CO_2 , except for September under offshore regimes, where ER was 28% larger than GPP. As a seasonal average, offshore ER/GPP was 67% higher than onshore ER/GPP.

The onshore/offshore light response curves (Fig. 6a) show little deviation from each other and are not significantly different ($p > 0.05$), using the Student-t test mentioned in the Method section. It is apparent that the sensitivity of GPP to PAR is the same regardless of air mass origin. However, for the same light levels, onshore conditions are cooler (Fig. 6b). This suggests that despite cooler temperatures, they are able to keep up with offshore GPP rates owing to enhanced onshore light levels. This suggests that the rates of ER between onshore and offshore wind regimes are more influential in the determination of NEE than GPP is.

The thermal response of the carbon flux is shown graphically for binned air temperatures for onshore and offshore wind regimes (Fig. 7a,b). Onshore GPP is consistently higher than offshore GPP at a given temperature, but the difference quickly diminishes after 20°C (Fig. 7a). Beyond 20°C offshore GPP experiences a slower increase, although values should be interpreted with caution as less data points were available for the averaging calculation at such high temperatures. NEE, comprising both GPP and ER, (Fig. 7b) shows a large difference between the onshore and offshore winds at the same temperature, with intermediate temperatures (11-20°C) demonstrating the largest difference in favour of onshore winds, which also coincides with the highest frequency of occurrence. Given that GPP values do not differ between onshore and offshore regimes at the same PAR (Fig. 6), other environmental factors that influence the carbon flux need to be considered. As Fig. 6b suggests, the origin of the air mass does not play a role in determining the strength of GPP, while it strongly influences the fate of ER through the apparent sensitivity of temperature through the covariance of PAR and temperature.

Discussion

Interplay Between Fluxes

The results of the interplay between GPP and ER under the influence of different environmental conditions reveals important aspects of the Hudson Bay Lowlands as a coastal environment where Hudson Bay's overall influence is intermittently imposed on the adjacent landscape, even up to 60 km inland as reported by Rouse and Bello (1985). The progression of daily average NEE over the growing season in 2007 was consistent with the pattern observed for other years at a nearby location (Lafleur *et al.* 2012). Although data presented here reflect ecosystem dynamics of a single year, the patterns are such that they are representative of the generic ecosystem function, although magnitudes may change inter-annually. At the beginning of the season, the flux was relatively strong ($-2 \mu\text{mol}/\text{m}^2/\text{s}$) even shortly after snowmelt, a process described by Aurela *et al.* (2002). Since a thin layer of snow can drastically alter the energy balance of an ecosystem, complete snowmelt allows for increased net radiation and the concurrent onset of photosynthesis, largely due to the presence of mosses and lichens (Oechel and Collins 1976). Bryophytes begin photosynthesizing immediately after snowmelt, making them important contributors earlier in the season before many vascular plants have leafed out. In September, the NEE abruptly dropped from its August levels, similar to Lafleur *et al.* (2012), indicating a quick senescence common to northern environments (Corradi *et al.* 2005; Lund *et al.* 2010). At this time of the year, daylength shortens, light levels decrease and temperatures are much cooler, unable to sustain strong photosynthesis.

Total GPP during the measurement period was 391 gC m^{-2} of which 66% occurred during onshore wind regimes, while responding to a number of environmental controls that mutually

contribute to stronger onshore CO₂ uptake. For the same temperature, onshore light levels consistently exceeded offshore levels, which was reflected in higher onshore GPP for any given temperature. The strong association between light levels and GPP with respect to marine origin air masses has also been documented by Lafleur and Rouse (1988). The onshore GPP strength for a given temperature, as shown in Fig. 7a, is directly translated into enhanced onshore NEE (Fig. 7b), as a direct consequence of the slope difference between onshore and offshore GPP rise with increasing temperatures.

The analysis reveals that GPP is less sensitive to temperature than ER, a result consistent with the findings of others (Billings *et al.* 1982; Silvola *et al.* 1996; and McGuire *et al.* 2000), regardless of air mass origin. Others report the opposite (McKane *et al.* 1997) or similar temperature sensitivities (Chivers *et al.* 2009), who attribute enhanced GPP in warmer soils to an increase in nutrient availability at Arctic tundra sites. In the current study, it is unlikely that changes in nutrient availability would accompany abrupt changes in air mass origin on a time scale of several hours. The results suggest that with increasing temperatures in the Arctic, the plant community will assimilate more CO₂ under onshore regimes compared to offshore regimes, if light level differences remain the same between the two regimes. Considering the small dataset representing temperatures beyond 20°C, it would be difficult to predict how light levels will change under a warming climate, requiring further research. Nevertheless, the Bay is associated with high pressure systems due to cooler temperatures and restricted moisture availability as a result of ice cover, contributing to clear skies under onshore regimes. This illustrates its strong influence on the surrounding coastal ecosystems, brought on by its current ice cover conditions.

Energy Balance and Permafrost

The partitioning of the coastal energy balance is expected to have a significant effect on the heat flow within the soil columns and within the boundary layer. The way energy is partitioned at the land surface directly influences the micrometeorological conditions of the ecosystem through the interaction between heat and moisture and potentially temperature and precipitation. Average net radiation does not show a difference between onshore and offshore regimes, but its partitioning into Q_E , Q_H and Q_G does. Although the mean onshore/offshore Q_E/Q^* is not statistically different, 46% of the growing season evaporation occurred when air masses were of marine origin. Rouse and Bello (1985) showed a similar pattern for their sea, near-coast and inland sites, illustrating the suppression of evaporation due to reduced vapor pressure gradients caused by the advective influence of moist cool air off Hudson Bay. The sensible heat flux increases strongly in response to cool air masses originating from the Bay, thereby lowering surface temperatures and removing energy that would have otherwise been utilized by Q_G for permafrost degradation. This, in turn, reduces the vertical temperature gradient into the soil suppressing the ground heat flux as a result of the Bay's presence (Rouse 2000). For tundra sites, a large proportion of summertime net radiation (~10-20%) is normally consumed in ground heating as a consequence of a sparse canopy and proximity of the frost table. (Lafleur *et al.* 1997; Eugster *et al.* 2000; Kellner 2001). The enhanced ground heating observed during offshore regimes increases soil temperatures and active layer growth, both contributing to heterotrophic decomposition, especially in soils comprised entirely of peat that house non-vascular plants (Callaghan *et al.* 2004). This is represented in the measured ecosystem respiration being especially sensitive to the changing wind direction and the air temperatures associated with those winds.

Expectations under a Warming Climate

In the mid 80's and 90's, northern latitudes were generally considered to be sinks for atmospheric CO₂ (Tans *et al.* 1990; Ciais *et al.* 2000) but with increasing global temperatures this may change. Extensive studies on carbon dynamics have demonstrated that temperature has an observed influence on NEE (Callaghan *et al.* 2004; Groendahl *et al.* 2007; Parmentier *et al.* 2011), although others have not found a strong link (Griffis *et al.* 2000; Aurela *et al.* 2004). As part of a dynamic system, there exist many nonlinear interacting processes within the carbon dynamical processes that would influence the net flux of carbon at the surface. But based on our field observations, we think there are two potential outcomes under a warming climate, where carbon sinks strengthen due to altered biogeochemical processes or where carbon stocks become sources due to increased respiration. Based on shown results, we expect the ecosystem to begin to undergo conditions typical of offshore wind regimes in a more pronounced fashion, characterized by higher temperatures, enhanced ground warming and active layer deepening, greater evaporation, and reduced light levels. The results presented here show that although offshore wind regimes produce GPP rates comparable to onshore, they are associated with a stronger increase in ER, making such regimes weaker sinks and supporting the second scenario.

Since higher temperatures are expected to prolong the growing season (Myneni *et al.* 1997) a shift in vegetation dynamics is to be expected alongside. This is anticipated to increase carbon stocks by accumulating newer and larger quantities of organic matter into the peat (Aurela *et al.* 2004; Euskirchen *et al.* 2006; Schuur *et al.* 2008). In accord with results presented in this study, Parmentier *et al.* (2011) conducted a multi-year analysis of NEE, GPP and ER, and concluded that longer growing season and warmer temperatures do not increase the NEE uptake

in their Siberian location, mainly a result of increased ER sensitivity to increased air temperatures in comparison to GPP; similar results were found by others (Dorrepaal *et al.* 2009; Cai *et al.* 2010). Consequently, northern ecosystems adapted to cold climate will not benefit by increased air temperatures with respect to carbon sequestration, as reinforced by our results and those of others (Fan *et al.* 2013). Instead, warmer air masses due to large-scale circumpolar warming are likely to skew the carbon flux towards increased respiration and decreased total carbon uptake during both onshore and offshore regimes. In addition to this global trend, the gradual disappearance of sea ice is expected to drive local and regional warming by altering the composition of the onshore air mass.

At the present time, the geographical situation of Hudson Bay predisposes it to having nearly complete year-round ice cover, except for two months. In August and September, the Bay is completely ice-free and summer and fall are characterized by 30-year negative sea-ice cover trends (Barber *et al.* 2012; Cavalieri and Parkinson 2012). This will have a significant influence on the atmospheric circulation regime over the Hudson Bay region. In addition to the influence of increasing global and regional temperatures on the make-up of onshore and offshore air masses, temperature is likely a driver for shifting winds. Positive temperature anomalies are correlated with negative sea-ice trends, most pronounced on the western and south-western part of the Bay, showing a decrease of 23.3% to 26.9% per decade since 1980 (Hochheim and Barber 2010). Evidence of changing wind regimes is presented by Hochheim *et al.* (2011), who found that anti-cyclonic atmospheric rotation occurs under high sea level pressure and low land surface pressure, resulting in onshore regimes. This pattern has been observed prior to 1989, whereas the post 1989 period is characterized by cyclonic atmospheric circulation which results from low sea level pressure and high land surface pressure, resulting in offshore winds. These results are

consistent with the qualitative indication of the decreasing frequency of onshore winds, compared to offshore winds (Fig. 8) during the month of June. The month of June behaves as a transitional month between ice-covered and ice-free water in Hudson Bay, and therefore is an indication of the encroaching offshore winds in the past, present and in the future. The decrease in onshore wind frequency will result in a weakened advective influence of Hudson Bay on the coastal Hudson Bay Lowlands, thereby increasing air and soil temperatures and decreasing the strength of the carbon sink. The conclusions reached are reinforced by those found by Rouse and Bello (1985) who identified a modest shift from onshore to offshore wind regimes as a result of advanced melting in the early growing season. The observed shift from onshore to offshore regimes in conjunction with melting sea ice will weaken the carbon sink of the coastal Hudson Bay Lowlands, in consequence reducing its capacity to sequester the increasing concentration of CO₂ in the atmosphere. A probable shift to more frequent offshore winds coupled with circumpolar scale air warming has significant implications for the degradation of permafrost through a deepening of the active layer, which has already been noted to occur (Payette et al. 2004).

During the 2007 growing season, the peat plateau experienced a substantial net gain of carbon, 116 gC/m². If the respiration before and after the growing season is accounted for by using the measured air temperatures from the Churchill airport (Environment Canada 2013) and using the respiration model described by Lloyd and Taylor (1994), the sequestered amount reduces to 27 gC/m²/year, which is relatively close to the long term value of 23 gC/m² /year estimated by Gorham (1991) for northern peatlands. Yet, this represents only 9.8% and 6.9% of annual GPP and ER, respectively, which is comparable to potential measurement errors. It is noteworthy that this coastal peat plateau comprises close to 50% vascular plant cover which is

not necessarily representative of ice-wedge polygon systems in general. Nevertheless, if this value is extrapolated to the entire area of the Hudson Bay Lowlands of 250,000 km², the uptake corresponds to 6.7 MtC/year. It is important to note the large uncertainty in extrapolating the carbon flux of a small area over the vast and heterogeneous ecosystems of the Hudson Bay Lowlands, however it does highlight the role tundra ecosystems in cold environments can play in mitigating anthropogenic emissions.

Conclusion

The difference in the CO₂ flux from upland tundra during onshore and offshore wind regimes was measured using the EC method in the Hudson Bay Lowlands near Churchill, MB. During the 2007 growing season, the peat plateau experienced a substantial net gain of carbon, 116 gC/m².

It was confirmed that the Hudson Bay has an advective influence on the carbon dynamics and energy balance of the coastal Hudson Bay Lowlands as others have concluded (Rouse and Bello 1985; Lafleur and Rouse 1988; Rouse *et al.* 1997). The CO₂ flux between the two wind regimes differed significantly, reinforcing the importance of Hudson Bay as mostly frozen water body dominated by onshore wind regimes. When normalized to PAR, there was no statistical difference between the GPP of onshore and offshore regimes, yet the offshore air temperature was significantly higher than the onshore air temperature. This suggests that although air temperatures have no effect on the difference of onshore and offshore GPP, ER is responsive to air mass origin. The strong response of ER is associated with different Q_H energy portioning, whereby onshore regimes remove energy that would otherwise warm the permafrost, while

offshore regimes add energy that contributes to permafrost degradation. This indicates a potential deterioration of the CO₂ budget of the Hudson Bay Lowlands under projected climate warming and sea ice reduction. As such, a better understanding of meso-scale wind regimes and sea ice dynamics under a warming climate is needed to have the ability to accurately project the future response of the coastal Hudson Bay Lowlands. Nevertheless, the observed shift from onshore to offshore regimes in conjunction with melting sea ice will weaken the carbon sink of the Hudson Bay Lowlands, in consequence reducing its capacity to sequester the increasing global emissions.

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Figure Captions

Fig. 1. Map of tower location and surrounding water bodies. Small ponds have been omitted. Inset: Location of Churchill Manitoba near the northern limit of the Hudson Bay Lowlands (black).

Fig. 2. Cumulative precipitation and evaporation rates (mm) over the study period.

Fig. 3. Mean monthly diurnal temperature curves for onshore and offshore wind regimes.

Fig. 4. Mean monthly energy balance for onshore and offshore wind regimes, as derived from mean monthly 30-minute daytime fluxes. September values are calculated until September 18th. Note the different axis scale for Q_G . Error bars represent standard error.

Fig. 5. Seasonal daily average NEE for data from all wind directions.

Fig. 6. (a) Binned light response curve for GPP for onshore and offshore wind regimes ($p > 0.05$). (b) Temperature response over binned light levels for onshore and offshore wind regimes ($p < 0.001$).

Fig. 7. (a) Daytime GPP and R (Lloyd and Taylor (1974) model) curves for binned air temperatures for onshore and offshore regimes. ER estimates are based on the same model for both wind directions due to the same model that was used. (b) Daytime NEE curves for binned air temperatures for onshore and offshore wind regimes.

Fig. 8. Changes in the proportion of onshore and offshore wind regime frequencies for June from 1953 to 2012. ($p = 0.06$).

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Table 1. Percent plant cover surrounding the EC tower within 100 m radius. Sampling methods are based on 50 cm x 50 cm quadrat sampling at 2 m intervals in 16 compass directions.

Plant Cover	Percent Cover
Understory	
Vascular	47.8
Lichen	25.4
Moss	23.2
Pond	1.0
Rock	2.7
Overstory	
Cloudberry	13.6
Birch	2.1
Willow	4.0
Evergreen	1.9

Table 2. Relative influence for four dominant plant covers (vascular, lichen, moss, cloudberry) computed for onshore and offshore wind directions. T-tests were performed, and a difference in magnitude is shown. Relative influence was computed using a weighted footprint model after Schuepp *et al.*, (1990). (* $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$).

		Relative Influence		Difference Magnitude
	Statistical Significance	Onshore	Offshore	
% Understory Vascular	*	33.12	32.51	1.02
% Understory Lichen	*	22.90	21.94	1.04
% Understory Moss	***	17.85	13.54	1.32
% Overstory Cloudberry	***	12.73	11.70	1.09

Table 3. Monthly precipitation (mm) and temperature (°C) for the study year of 2007 and historical average (HA) values. Bracketed terms show one standard deviation.

	June		July		August		September (until 18 th)	
	2007	HA	2007	HA	2007	HA	2007	HA
Precipitation (mm)	48.2	44.3	30.2 2	56	44.4	68.3	70.6	63.4
T (°C)	5.9	6.6 (2.1)	15.4	12 (1.7)	12	11.7 (1.5)	5.4	5.6 (1.8)

Table 4. Energy balance components as proportions of net available energy for onshore (ON) and offshore (OFF) wind regimes for the four study months, as derived from 30-minute daytime fluxes. SS-statistical significance. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

	Q_E/Q^*			Q_H/Q^*			Q_G/Q^*		
	ON	OFF	SS	ON	OFF	SS	ON	OFF	SS
June	0.46	0.41	-	0.61	0.44	**	0.05	0.05	-
July	0.49	0.58	-	0.45	0.23	***	0.09	0.17	**
August	0.61	0.63	-	0.28	0.11	**	0.10	0.13	*
September	0.69	0.40	-	0.11	0.38	*	0.12	0.26	-
Season	0.46	0.53	-	0.44	0.26	***	0.08	0.14	**

Table 5. (a) Monthly and seasonal flux means and flux normalized to PAR for onshore and offshore wind regimes, as derived from 30-minute daytime fluxes. (b) Ratios of offshore to onshore (OFF/ON) represent % difference with associated statistical test. SS-statistical significance. * P<0.05; ** P<0.01; *** P<0.001.

(a)	GPP ($\mu\text{mol}/\text{m}^2/\text{s}$)		ER ($\mu\text{mol}/\text{m}^2/\text{s}$)		NEE ($\mu\text{mol}/\text{m}^2/\text{s}$)		T ($^{\circ}\text{C}$)		GPP/PAR ($\mu\text{mol CO}_2 / \mu\text{mol photons}$)		ER/PAR ($\mu\text{mol CO}_2 / \mu\text{mol photons}$)		ER/GPP	
	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
June	3.69 ± 0.07	4.17 ± 0.10	1.53 ± 0.02	2.21 ± 0.04	-2.16 ± 0.07	-1.91 ± 0.09	4.93	9.70	0.73	0.80	0.46	0.57	0.53	0.63
July	7.29 ± 0.11	7.02 ± 0.19	3.31 ± 0.04	4.31 ± 0.06	-3.95 ± 0.10	-2.49 ± 0.16	14.39	19.46	1.28	1.69	0.83	1.58	0.55	0.78
August	6.35 ± 0.11	5.83 ± 0.14	2.82 ± 0.02	3.40 ± 0.05	-3.54 ± 0.11	-2.47 ± 0.14	11.66	14.59	1.20	1.58	0.74	1.33	0.56	0.93
September	3.58 ± 0.11	4.17 ± 0.18	1.75 ± 0.03	2.48 ± 0.06	-1.80 ± 0.10	-1.55 ± 0.16	5.28	9.58	1.15	1.19	0.82	1.15	0.71	1.28
Season	5.43 ± 0.06	5.45 ± 0.09	2.42 ± 0.02	3.19 ± 0.04	-3.00 ± 0.05	-2.20 ± 0.07	9.52	13.67	1.07	1.35	0.68	1.17	0.60	0.99

(b)	GPP		ER		NEE		T ($^{\circ}\text{C}$)		GPP/PAR		ER/PAR		ER/GPP	
	OFF/ ON Mean	SS	OFF/ ON Mean	SS	OFF/ ON Mean	SS	$^{\circ}\text{C}$ higher for OFF	SS	OFF/ ON Mean	SS	OFF/ ON Mean	SS	OFF/ ON Mean	SS
June	1.13	***	1.45	***	0.88	*	4.77	***	1.09	-	1.26	**	1.18	***
July	0.96	-	1.30	***	0.63	***	5.07	***	1.32	***	1.91	***	1.43	***
August	0.92	**	1.20	***	0.70	***	2.93	***	1.31	***	1.80	***	1.65	**
September	1.16	-	1.42	***	0.86	-	4.30	***	1.04	-	1.40	***	1.81	**
Season	1.00	-	1.32	***	0.73	***	4.15	***	1.26	***	1.71	***	1.67	***