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Carbon dioxide and methane annual emissions from two boreal reservoirs and nearby lakes in Quebec, Canada

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Abstract

The results of dissolved GHG (CO_2 and CH_4) measurement campaigns carried out in Quebec (Canada) during the open-water periods and under-ice in a newly created reservoir (Eastmain 1), a 25 year old reservoir (Robert-Bourassa) and in three reference lakes are presented. While CO_2 partial pressures varied with season with a net increase under the ice cover, CH_4 partial pressures did not. We were able to extrapolate the highest CO_2 partial pressures reached in the different studied systems just before ice break-up with high spring emission period. We then estimated the springtime CO_2 fluxes and compared them to annual CO_2 fluxes and GHG fluxes. Thus we clearly demonstrated that in our systems CH_4 fluxes was of minor importance in the GHG emissions, CO_2 fluxes representing around 90% of the annual fluxes. We also pointed out the importance of springtime emissions in the annual budget.

1 Introduction

The implication of freshwater ecosystems in the global carbon budget has been neglected for a long time because of their weak surface coverage at the Earth's scale compared to forest or oceans. However a recent study of Cole et al. (2007) demonstrates that lakes, reservoirs and rivers do not behave as simple pipes transporting organic matter from terrestrial systems to oceans. Actually, half of the carbon annually entering freshwater ecosystems is thereby buried and will never reach the ocean.

It has also been demonstrated that the loading of terrestrial dissolved organic carbon can contribute significantly to the energy pathways of lake ecosystems (Tranvik 1992; Pace et al., 2004; Carpenter et al., 2005; Kritzberg et al., 2006) sometimes leading to respiration rates exceeding production rates (Del Giorgio et al., 1997). This process, also named heterotrophy, is believed to be largely responsible for the CO_2 supersaturation observed in most lakes of the world (Cole et al., 1994, Sobek et al., 2003; Del Giorgio et al., 1999; Duarte and Prairie, 2005).

Freshwater ecosystems thus clearly appear as preferential sites for carbon emissions to the atmosphere. Direct flux measurements and flux calculations from partial pressures (MacIntyre et al., 1995) measured during summertime are performed since the 1990's in the northern hemisphere and are now becoming common practice in the tropical zones as well (Tremblay et al., 2005). In fact, comprehensive understanding of the processes involved in the global carbon cycle is crucial for fundamental research, and evaluation of net GHG emissions from reservoirs and natural systems is becoming more and more crucial to ensure accurate comparisons of energy production methods, evaluation of CO_2 credits, and determination of national GHG Inventories (IPCC, 2006).

In north temperate and boreal regions, seasonal variations in carbon emissions (CO_2 and CH_4) from freshwater ecosystems are difficult to measure because the ice cover during wintertime prevents direct flux measurements with floating chambers, and continuous monitors such as Eddy Covariance Towers still provide unreliable measurements on lakes and reservoirs (interferences with surrounding forest for example; MacIntyre et al., 1995; Eugster et al., 2003). In parallel to the study presented here, we propose the use of a single automated system installed in generating stations to measure CO_2 and CH_4 partial pressures in continuous and therefore calculate potential fluxes from reservoirs during the ice free period and monitoring gas concentrations all the year through (Demarty et al., 2009). However, these devices are still needed to be adapted to operate on a stand-alone basis for monitoring on lakes in winter. Field campaigns at different seasons are consequently the only way, at the moment, to figure annual trends in carbon emissions of natural freshwater ecosystems. Because of the difficulties encountered during wintertime sampling, few exhaustive studies reports the trends in CO_2 and CH_4 concentrations under ice cover. However it is commonly recognized that these gases accumulate under the ice and are released upon spring ice break-up (Riera et al., 1997; Duchemin et al., 2006; Kortelainen et al., 2000; Michmerhuizen and Striegl, 1996; Striegl et al., 2001; Huttunen et al., 2004). In overall gross emissions of boreal reservoirs, degassing and bubble fluxes are very small (Tremblay et al., 2005; Roehm and Tremblay, 2006; Tremblay and Bastien, 2009), therefore we only present here, results from summertime and wintertime field campaigns of diffusive CO_2 and CH_4 fluxes. We address the question of the gas accumulation under ice cover in both lakes and reservoirs and we proposed a way to estimate maximum springtime fluxes in order to provide conservative annual greenhouse gas fluxes.

2 Material and methods

2.1 Study sites

Sampling stations are located in the boreal zone, north-west Quebec, Canada. Eastmain 1 Reservoir (52.19° N; 75.05° W; created in 2005), Mistumis Lake (52.16° N; 76.16° W) and Clarkie Lake (52.23° N; 75.47° W) are in the Eastmain River hydraulic system. Robert-Bourassa Reservoir (53.78° N; 77.53° W; created in 1979), Yasinski Lake (53.28° N; 77.53° W) and Duncan Lake (53.49° N; 77.89° W) are in the La Grande River hydraulic system. Sampling dates and number of sampling stations for each system are described in Table 1. The catchments of Robert-Bourassa and Eastmain 1 areas are dominated by coniferous forest, shallow podzolic and peat soils, and igneous bed rock. They are described as oligotrophic systems with an overall low primary production. The studied reservoirs and lakes are partially to totally covered by ice from 15 December to 15 May approximately.

2.2 Temperature and dissolved oxygen

Temperature and dissolved oxygen saturation profiles were performed at each sampling station for Eastmain 1 Reservoir and Mistumis Lake (YSI 600). Samples were taken at each meter for stations under 10 m deep and each two meter for stations above 10 m deep. In order to obtain a broad description of the studied water bodies among field campaigns, we averaged data obtained at each sampling depth and thus obtained mean profiles.

Eastmain 1 Reservoir and Robert-Bourassa Reservoir water temperatures were also measured continuously by automated systems installed inside the corresponding generating stations (Eastmain 1 and LG-2; Demarty et al., 2009). These temperatures are assumed to be representative of the whole reservoir temperature and also of the studied lakes nearby.

2.3 CO_2 and CH_4 partial pressures

CO_2 and CH_4 water partial pressures were measured at the water surface (0.1 m) and for some stations profiles were performed (3 depth chosen according to the station water depth), water being sampled with a peristaltic pump. At Eastmain 1 Reservoir, $p\mathrm{CO}_2$ and $p\mathrm{CH}_4$ profiles were made for 11 sampling stations in March 2007, 17 in January 2008, 16 in March 2008, 14 in July 2008 and 9 in September 2008. At Mistumis Lake $p\mathrm{CO}_2$ and $p\mathrm{CH}_4$ profiles were made at one station for each field campaign. Water $p\mathrm{CO}_2$ was measured in situ with a Non Dispersive Infra Red (NDIR) sensor (EGM-4 from PP-Systems) coupled with a gas exchanger (Celgard from Membrana) (Fig. 1). Ten consecutive measurements (one per minute) were averaged to obtain the $p\mathrm{CO}_2$ at each station.

Water samples for determination of water $p\mathrm{CH}_4$ were collected after the gas exchanger; this device had no effect on the measurements (Student paired test with samples collected before and after the water passed through the exchanger, $p>0.05$, data not shown). Three samples of 30 mL were collected in 60 mL polypropylene syringes from each depth and chilled in a dark cooler for transport to the laboratory. There, 30 mL of nitrogen gas (N_2) was added. Water and N_2 were equilibrated by shaking the syringe vigorously for 2 min. Headspace CH_4 partial pressure ($p\mathrm{CH}_4 HS$) was quantified on a gas chromatograph having a thermal conductivity detector. Partial pressure before equilibration ($p\mathrm{CH}_4 f$) is determined from Eq. (1):

$$p\mathrm{CH}_4 f = \frac{\left(p\mathrm{CH}_4 HS * K_{H\,Eq.}\right) + \left(1 * \frac{(p\mathrm{CH}_4 HS - p\mathrm{CH}_4 i)}{V_m}\right)}{K_{H\,\mathrm{Sample}}} \qquad (1)$$

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where $K_{H\,Eq.}$ and $K_{H\,\mathrm{Sample}}$ are the gas partition constants at equilibrium (20°C) and at sampling temperature, respectively, in mol L^{-1} atm^{-1}, calculated according to Lide, 2007; $p\mathrm{CH}_4 i$ is equal to zero, since the only gas present in the air inside the syringe before equilibration was N_2; and V_m is the molar volume (according to Avogadro's law). The field $p\mathrm{CH}_4$ was obtained in averaging the three replicates.

2.4 CO_2 and CH_4 fluxes

We calculated mean $p\mathrm{CO}_2$ and $p\mathrm{CH}_4$ for ice free periods and springtime and thus estimated mean fluxes, using corresponding mean water temperature (data from automated systems at Eastmain 1 and Robert-Bourassa GS) and wind speeds (data from Nemiscau Airport meteorological station for Eastmain River system and La Grande River Airport meteorological station for La Grande River system).

Flux calculations require conversion of the partial pressures in concentration. CO_2 water concentration ($\mathrm{CO}_2 wc$) was calculated from $p\mathrm{CO}_2$ ($\mathrm{CO}_2 wp$) according to Eqs. (2 and 3):

$$\mathrm{CO}_2 wc = K_H * \mathrm{CO}_2 wp \tag{2}$$

with:

$$\ln K_H(\mathrm{CO}_2) = -58.0931 + 90.5069 * \left(\frac{100}{T_K}\right) + 22.294 * \ln\left(\frac{T_K}{100}\right) \tag{3}$$

where $K_H(\mathrm{CO}_2)$ is the solubility of CO_2 in water expressed in mole L^{-1} atm^{-1}, T_K is the water temperature in Kelvin (Weiss, 1974).

CH_4 water concentration ($\mathrm{CH}_4 wc$) was calculated from $p\mathrm{CH}_4$ ($\mathrm{CH}_4 wp$) according to Eqs. (4 and 5):

$$\mathrm{CH}_4 wc = K_{H\,\mathrm{Sample}} * \mathrm{CH}_4 wp \tag{4}$$

with:

$$\ln K_H(\mathrm{CH}_4) = -115.6477 + \frac{155.5756}{(T_K/100)} + 65.2553 * \ln\left(\frac{T_K}{100}\right) - 6.1698 * \left(\frac{T_K}{100}\right) \tag{5}$$

where T_K is the water temperature in degree Kelvin (Weiss, 1974).

CO_2 and CH_4 fluxes are given by Eq. (6) (MacIntyre et al., 1995), k_x being the Mass Transfer Coefficient calculated according to Cole and Caraco (1998):

$$\text{Flux} = k_x(Cwc - \alpha Cac) \tag{6}$$

where αCac is the gas concentration in water exposed to the atmosphere calculated from Eqs. (3 and 5) and global mean atmospheric partial pressure (385 µatm for CO_2, NOAA October 2008; and 1.745 µatm for CH_4, Houghton et al., 2001).

The GHG flux is the sum of the CO_2 flux plus the CH_4 flux in CO_2eq (Eq. 7). The CH_4 flux in CO_2eq is calculated using its Global Warming Potential of 23 (Houghton et al., 2001).

$$\text{GHG flux}(CO_2eq) = CO_2\text{ flux} + 23 * (CH_4\text{ flux}) \tag{7}$$

3 Results

3.1 Temperature and dissolved gases profiles

We observed no temperature stratification for both Eastmain 1 Reservoir and Mistumis Lake whatever the season (Fig. 2a and b). Because of the absence of hypolimnetic waters in these water bodies, it is not surprising to observe no oxicline even if dissolved oxygen saturation slightly decreased with depth at all seasons (Fig. 2c and d). In July 2007 at Eastmain 1 Reservoir only one or two sampling stations have been sampled under 8 m deep; therefore the observed anoxia is not representative of the whole reservoir. There was a general increase in pCO_2 with depth at Eastmain 1 Reservoir whatever the season, with highest values observed in January and March (Fig. 2e and f). At Mistumis Lake, this increase with depth is observed in January and March but not in July or September. Except high values observed at single sampling stations during March 2007 and 2008 field campaigns, pCH_4 presented no trends with depth (Fig. 2g and h).

3.2 Seasonal trends in mean surface water pCO_2 and pCH_4

Under the assumption of an atmospheric CO_2 concentration of 385 µatm, we observe that the six studied water bodies are supersaturated in CO_2 whatever the season, with pCO_2 being from 1 (Clarkie Lake, September 2008) to 7 (Eastmain 1 Reservoir, March 2007) times higher than the atmospheric concentration. For Eastmain 1 Reservoir, Mistumis Lake and Clarkie Lake mean surface pCO_2 measured during 2007 and 2008 spring campaigns (in March) are clearly higher than those measured in July 2006, 2007 and 2008, September 2006 and 2008 and in January 2008, approximately 1.5 month after the ice cover formation (ANOVA, $p<0.05$; Table 2 and Fig. 3). For statistical analysis March and April data for Robert-Bourassa Reservoir, Yasinski Lake and Duncan Lake have been pooled, since they did not present significant difference (Student Test, $p<0.05$; Table 2). Thus, winter surface pCO_2 at Robert-Bourassa reservoir and Yasinski Lake are higher than during summer (Student Test, $p<0.05$; Fig. 3), whereas it is not the case for Duncan Lake (Student Test, $p>0.05$).

In July 2006, the first year after Eastmain 1 Reservoir creation, surface pCO_2 measured are higher than in July 2007 and July 2008.

No difference in surface pCH_4 measured at Eastmain 1 Reservoir, Mistumis Lake, or Clarkie Lake among field campaigns were observed (ANOVA and Tukey test, $p>0.05$). For subsequent calculations, it is therefore considered that there was no CH_4 accumulation under the ice cover in the studied systems. PCH_4 was measured at Robert-Bourassa Reservoir, Yasinski Lake and Duncan Lake only during the April 2006 field campaign; we will therefore consider a constant pCH_4 throughout the year for subsequent estimations.

The highest pCO_2 and pCH_4 values were measured at Eastmain 1 Reservoir.

3.3 Estimation of the maximum dissolved pCO_2 reached before ice break-up

Our results above showed a CO_2 accumulation under the ice cover in all the water bodies sampled (Eastmain 1 and Robert-Bourassa reservoirs, lakes Mitsumis, Clarkie and Yasinski). No difference in summer, autumn and early winter (until January) in mean dissolved $p\mathrm{CO}_2$ was observed. Once grouped, these data thus represent the baseline $p\mathrm{CO}_2$ of the year. We observed higher dissolved $p\mathrm{CO}_2$ in March than in January and a linear increase of dissolved $p\mathrm{CO}_2$ is expected under the ice cover from January to May, time when ice break-up occurs.

Linear regressions between baselines $p\mathrm{CO}_2$ and March $p\mathrm{CO}_2$ have been made to calculate springtime daily rate of $p\mathrm{CO}_2$ increase under the ice, respectively (75 days between 15 January and 30 March; Table 3). Considering the date of 15 May as the beginning of ice free emission period (after observations from automated systems, Demarty et al., 2009), we thus estimated maximum potential $p\mathrm{CO}_2$ before ice break-up. Our goal being to obtain a broad estimation of the potential springtime CO_2 flux of Robert-Bourassa Reservoir and Yasinski Lake for which we have only one summer field campaign and two winter field campaigns (2006), 2005 baseline $p\mathrm{CO}_2$ was assumed to be equal to 2006 baseline $p\mathrm{CO}_2$. From these calculations, it is clear that the Eastmain 1 Reservoir tend to present the highest $p\mathrm{CO}_2$ before the spring emission period (Table 3).

3.4 Estimation of the potential springtime GHG emission

The high spring emission period in the studied areas was observed in the field to last around one month, from 15 May to 15 June. Between these dates, fluxes were assumed to follow a linear trend. Maximum potential gas partial pressures were used to calculate the maximum potential fluxes at the beginning of the degassing period and baseline gas partial pressures were used to calculate potential fluxes during the following period (summer and fall; Table 4). Averaging these two fluxes, we obtained a mean daily springtime flux, which is used to compute an annual carbon budget.

3.5 Annual cumulative diffusive fluxes

The annual CO_2 flux has been considered as the sum of the daily fluxes between two degassing periods (for example 15 May 2007 to 15 May 2008); thus we add 31 days of mean springtime flux (see Table 4), 214 days of mean ice free period flux (summer, autumn and beginning of winter), and 120 days without flux (ice covered period). Resulting annual CO_2 evasions for studied water bodies are presented in Table 5. Springtime CO_2 fluxes represented 16% (Yasinski Lake) to 52% (Mistumis Lake) of the annual CO_2 emission and springtime CH_4 fluxes represented 5% (Eastmain 1 Reservoir) to 18% (Clarkie Lake) of the annual CH_4 emission.

3.6 Discussion

This study is the first to provide a multi-annual estimation of springtime GHG diffusive fluxes for both reservoirs and control lakes in the same area. The potential springtime GHG flux of lakes and reservoirs is commonly calculated using the potential GHG storage of water bodies integrated versus depth to obtain concentration per square meter; fluxes are then calculated by comparing these concentrations to the theoretical dissolved gas concentration at the equilibrium with the actual atmosphere (around 14 µmol or 385 µatm; Michmerhuizen and Striegl, 1996; Striegl and Michmerhuizen, 1998; Striegl et al., 2001; Huttunuen et al., 2004; Duchemin et al., 2006), therefore overestimating annual CO_2 emissions and the winter contribution. However, CO_2 supersaturation is described for lakes around the world (Cole et al., 1994; Sobek et al., 2003; Del Giorgio et al., 1999; Duarte and Prairie, 2005) and also for reservoirs (Tremblay et al., 2005; Demarty et al., 2008), meaning that their concentration are generally above atmospheric concentration and oversaturated the major part of the year. In this article we support the use of the difference in partial pressure at the beginning and at the end of the ice cover period as a more relevant method to estimate springtime fluxes.

Two main assumptions were made regarding the estimation of the maximum dissolved gas partial pressures before ice break-up. First, our field measurements showed dissolved CO_2 accumulation between January and March, thus suggesting that ice formation over the entire water body takes few weeks up to the beginning of January. This is confirmed by the La Grande and Eastmain ice follow up that indicate the ice reach a thickness of about 20 cm by the end of December. For safety reasons, field campaign can only be conducted between early January and the end of March when ice is at least 20 cm thick. Therefore, the baseline fluxes, averaging summer, autumn and early winter fluxes, were used until the end of December to compute a conservative annual flux. Secondly, we assumed a linear trend in CO_2 accumulation under the ice from January until the beginning of the emission period and a linear decrease during spring. These trends are supported by the results obtained from automated systems providing us continuous $p\mathrm{CO}_2$ and $p\mathrm{CH}_4$ measurements at Eastmain 1 Reservoir and Robert-Bourassa reservoirs since 2007 (Demarty et al., 2009). From the ice follow-up program over the last 30 years, we observed that the emission period began around one month after the beginning of the ice break-up, thus showing that not only ice break-up but principally springtime water column mixing are responsible for high spring emission.

Except for Duncan Lake, we observed CO_2 accumulation under the ice cover for both studied lakes and reservoirs. This suggests bacterial activity during winter. The springtime daily rates of CO_2 increase under the ice cover presented in Table 3 were calculated in terms of concentration rather than partial pressure (Table 6; calculation according to Eqs. (1 and 4), considering a surface temperature of 0.1°C, according to field observations). Rates varied between 0.23 and 0.92 $\mu g\,C\,L^{-1}\,h^{-1}$ at Yasinski Lake and Eastmain 1 Reservoir, respectively. In their review about respiration in lakes, Pace and Prairie (2005) summarize field observations of planktonic respiration, which vary between 0.35 $\mu g\,C\,L^{-1}\,h^{-1}$ and 81.07 $\mu g\,C\,L^{-1}\,h^{-1}$ (mean: 7.85 $\mu g\,C\,L^{-1}\,h^{-1}$); temperature is presented as an important factor influencing these respiration rates. Interestingly, the observed CO_2 increase rates observed under the ice in our systems are comparable to the lower range reported by Pace and Prairie. This strongly suggests that CO_2 increase under the ice is due to normal bacterial respiration under the influence of cold temperatures. This idea is supported by the study of Striegl et al. (2001), which demonstrate that high dissolved $p\mathrm{CO}_2$ prior the ice melt is related to bacterial respiration. Moreover, highest $p\mathrm{CO}_2$ and wintertime CO_2 increase rates was observed at Eastmain 1 Reservoir. This was expected since it is a young reservoir flooded 3 years ago (in 2006). Flooding of large quantity of organic matter lead to an increase in dissolved $p\mathrm{CO}_2$ through an increase in bacterial activity (Tremblay et al., 2005; Tadonkélé et al., 2005). After an initial peak, generally reached within the first five years after flooding, CO_2 fluxes and CO_2 concentrations decrease to reach values comparable to natural aquatic ecosystems within a period of 10 years, (Tremblay et al., 2005). After this transition period (<10 years), CO_2 emissions are related to the carbon entering the reservoir as runoff from the watershed, the reservoir effect is over after that period. In the case of the Eastmain 1 Reservoir, the return to natural aquatic ecosystems values was faster, it was reached the third year after flooding (2008) (Tremblay et al., 2009; Tremblay and Bastien, 2009).

Accordingly with the facts that the water column is well oxygenated from the surface to the bottom and that most of the CH_4 produced in the anoxic sediment is oxidised at the sediment-water interface (Frenzel et al., 1990) and that CH_4 escaping from the sediment-water interface would be slowly oxidised in the water column, no clear CH_4 accumulation was observed under the ice. The same trends were observed by Huttunen et al. (2004) in a small boreal lake during three consecutive late winters. Similar results were also observed in 4 reservoirs in Manitoba over 3 years and 3 reservoirs over 18 months in Québec with automated systems measuring CO_2 and CH_4 from power house (Demarty et al. 2009).

Our results clearly show that diffusive CH_4 emissions are not of concern in the studied systems, which contradicts what was suggested by Duchemin et al. (2006). In their study, Duchemin et al. (2006) have collected very few samples in very shallow (<2 m) and small impounded bays with limited water exchange with the major reservoir water body. Shallow areas of reservoir would be the most appropriate environment for CH_4 production with warmer water temperature (>15 °C in summer time). However, most of the reservoir shallow areas are situated around the reservoir, where the organic matter is eroded within the first 5 years, to mineral horizon or the bedrock, by wind and ice action and water level fluctuation related to electricity generation. Therefore CH_4 production in shallow areas is very limited and the results from Duchemin et al. (2006) cannot be extrapolated to large reservoirs.

Lakes potential springtime GHG emissions (presented in Table 4) are in the same order than what was measured in a boreal lake by Huttunen et al. (2004; 103 to 128 $\mathrm{g\,CO_2}eq\,\mathrm{m^{-2}}$). Springtime GHG emissions represented 16% to 52% of the annual GHG emission, which is above what was reported by Duchemin et al. (2006), where springtime GHG flux represented only 7% of the annual flux at Robert-Bourassa Reservoir. However, our results are more consistent since they better represent the spatial variability of the studied water bodies (higher number of sampling stations). Our results also demonstrate that generally >90% of annual GHG emissions are carbon dioxide.

4 Summary

We provide results from exhaustive surveys of GHG partial pressure and fluxes in both lakes and reservoirs in north-western Quebec, which allow us to estimate reliable springtime GHG fluxes from few assumptions. We also demonstrated that during wintertime, the CO_2 increase rates measured under the ice cover are equivalent to bacterial respiration rates measured in lakes, thus highly suggesting a link between both processes in our systems. We finally found that springtime GHG emissions represent a higher proportion of the annual GHG emissions than what was previously proposed, CO_2 being largely responsible of the total annual emissions.

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Table 1. Sampling periods and number of sampled stations for each studied water body.

Systems	Sampling periods	Number of sampling stations		
		Eastmain 1 Reservoir	Mistumis Lake	Clarkie Lake
Eastmain River	10 to 22 Jul 2006	41	3	2
	18 Sep to 4 Oct 2006	42		
	20 to 27 Mar 2007	39	3	
	5 to 21 Jul 2007	38	3	3
	14 to 26 Jan 2008	42	3	3
	26 Mar to 5 Apr 2008	35	3	2
	3 to 22 Jul 2008	57	3	3
	15 to 22 Sep 2008	27	3	2
		Robert-Bourassa Reservoir	Yasinski Lake	Duncan Lake
La Grande River	25 Feb to 4 Mar 2006	17	1	3
	4 to 11 Apr 2006	29	3	4
	24 to 27 Jul 2006	14	2	2

Table 2. Mean surface $p\text{CO}_2$ and $p\text{CH}_4$ measured at Eastmain 1 Reservoir, Mistumis Lake, Clarkie Lake, Robert-Bourassa Reservoir, Duncan Lake and Yasinski Lake.

Field campaigns	Eastmain 1 Reservoir		Mistumis Lake		Clarkie Lake		Robert-Bourassa Reservoir		Duncan Lake		Yasinski Lake	
	$p\text{CO}_2$	$p\text{CH}_4$	$p\text{CO}_2$	$p\text{CH}_4$	$p\text{CO}_2$	$p\text{CH}_4$	$p\text{CO}_2$	$p\text{CH}_4$	$p\text{CO}_2$	$p\text{CH}_4$	$p\text{CO}_2$	$p\text{CH}_4$
						µatm (or ppm)						
Mar 2006	–	–	–	–	–	–	870±186	–	650±80	–	750	–
Apr 2006	–	–	–	–	–	–	803±204	59±189	580±20	9±1	810±20	20±17
Jul 2006	2230±563	125±151	565±30	33±5	558±13	–	560±149	–	540±80	–	661±24	–
Sep 2006	2181±485	83±65	–	–	–	–	–	–	–	–	–	–
Mar 2007	2798±708	20±31	1441±47	8±2	–	–	–	–	–	–	–	–
Jul 2007	1333±317	–	568±47	–	496±42	–	–	–	–	–	–	–
Jan 2008	1211±194	40±82	856±25	17±2	716±31	11±1	–	–	–	–	–	–
Mar 2008	2529±796	287±982	1533±268	19±9	975±171	13±2	–	–	–	–	–	–
Jul 2008	1025±361	58±56	620±73	25±19	507±34	9±2	–	–	–	–	–	–
Sep 2008	1340±459	38±38	454±18	24±7	425±4	17±5	–	–	–	–	–	–

Table 3. Daily rates of springtime pCO_2 increase and maximum potential pCO_2 reached the 15 May at Eatmain 1 Reservoir and Mistumis Lake.

Studied systems	n	Springtime daily rates of pCO_2 increase µatm d^{-1}	SD µatm d^{-1}	R^2	Maximum potential pCO_2 reached (15 May)
Eastmain 1 Reservoir 2007	122	8	17	0.8	3154
Eastmain 1 Reservoir 2008	116	17	14	0.59	3285
Mistumis Lake 2007	7	12	1	0.99	1967
Mistumis Lake 2008	9	11	6	0.83	2026
Clarkie Lake 2008	8	5	4	0.65	1196
Robert-Bourassa Reservoir 2006	60	4	6	0.52	987
Yasinski Lake 2006	6	2	1	0.85	875

Table 4. Springtime CO_2, CH_4 and GHG fluxes. The beginning and the end of the degassing periods are assumed to be around 15 May and 15 June, respectively.

Water body	Degasing period	CO_2 flux (mmol m^{-2} d^{-1})	CH_4 flux (mmol m^{-2} d^{-1})	Mean CO_2 springtime flux (mmol m^{-2} d^{-1})	Mean CH_4 springtime flux (mmol m^{-2} d^{-1})	Mean GHG springtime flux (mmol CO_2eq m^{-2} d^{-1})	Total GHG springtime flux (g CO_2eq m^{-2})
Eastmain 1 Reservoir	Beginning – 2007	131	0.017	86	0.017	86	117
	End – 2007	40	0.017				
	Beginning – 2008	173	0.059	108	0.036	108	147
	End – 2008	43	0.012				
Mistumis Lake	Beginning – 2007	75	0.010	45	0.010	45	61
	End – 2007	15	0.010				
	Beginning – 2008	98	0.036	53	0.043	53	73
	End – 2008	9	0.049				
Clarkie Lake	Beginning – 2008	49	0.023	27	0.019	27	37
	End – 2008	5	0.015				
Robert-Bourassa Reservoir	Beginning – 2006	34	0.110	22	0.110	22	30
	End – 2006	10	0.110				
Yasinski Lake	Beginning – 2006	28	0.035	21	0.035	21	29
	End – 2006	15	0.035				

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Table 5. Ice free period, springtime and annual CO_2, CH_4 and GHG emissions for the studied water bodies.

Studied water bodies	CO_2				CH_4				GHG	
	Ice free period CO_2 emission	Springtime CO_2 emission mmol m^{-2}	Annual CO_2 emission	Spring flux/ annual flux %	Ice free period CH_4 emission	Springtime CH_4 emission mmol m^{-2}	Annual annual flux	Spring flux/ CH_4 emission %	Annual GHG emissions g CO_2eq m^{-2}	CO_2 contribution %
Eastmain 1 Reservoir 2007–2008	8747	2654	11 401	23	7	1	7	7	509	98.6
Eastmain 1 Reservoir 2008–2009	7374	3348	10 723	31	20	1	21	5	493	95.6
Mistumis Lake 2007–2008	3248	1392	4640	30	2	0	3	12	207	98.8
Mistumis Lake 2008–2009	1528	1658	3186	52	8	1	10	13	150	93.5
Clarkie Lake 2008–2009	903	834	1737	48	3	1	3	18	80	95.9
Robert-Bourassa Reservoir 2006–2007	2208	676	2884	23	26	3	29	11	156	81.2
Yasinski Lake 2006–2007	3448	664	4112	16	8	1	9	11	190	95.1

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Table 6. Wintertime rates of CO_2 increase.

Water body*	Eastmain 1 Reservoir		Mistumis Lake		Clarkie Lake	Robert-Bourassa Reservoir	Yasinski L.
Period	Winter 2007	Winter 2008	Winter 2007	Winter 2008	Winter 2008	Winter 2006	Winter 2006
Rate of CO_2 increase under ice cover $\mu g\,C\,L^{-1}\,h^{-1}$	0.76	0.92	0.59	0.57	0.32	0.28	0.23

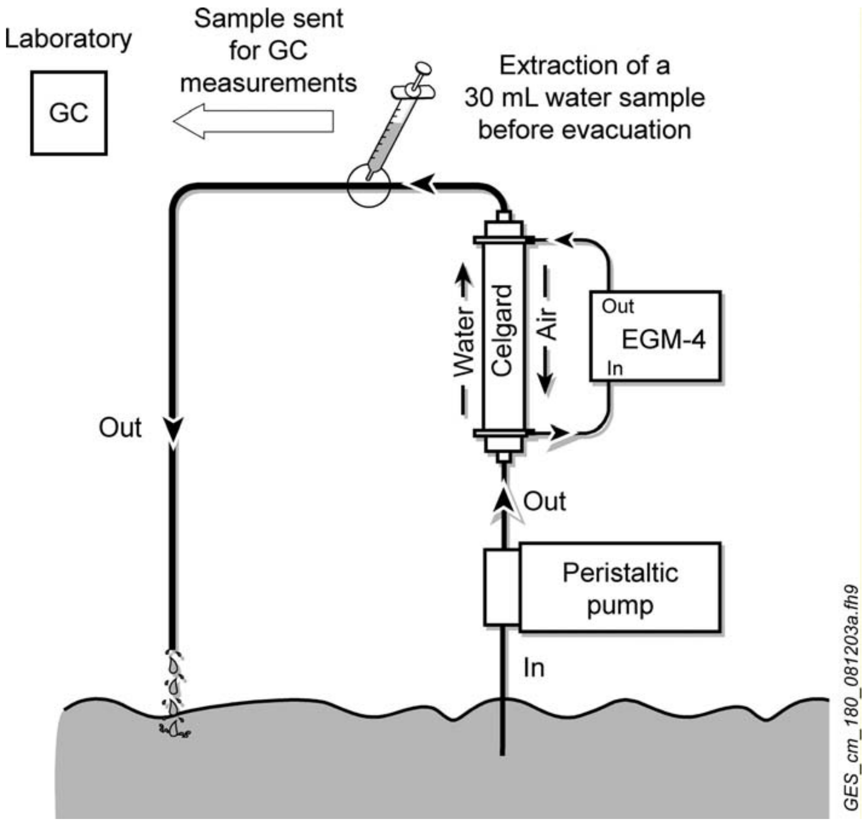

Fig. 1. Experimental setup.

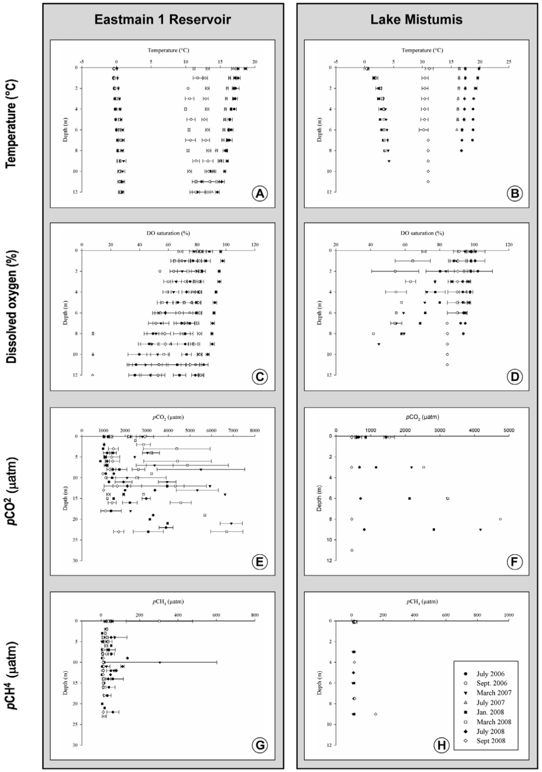

Fig. 2. Temperature, dissolved oxygen, pCO_2 and pCH_4 mean profiles with depth at Eastmain 1 Reservoir and Mistumis Lake.

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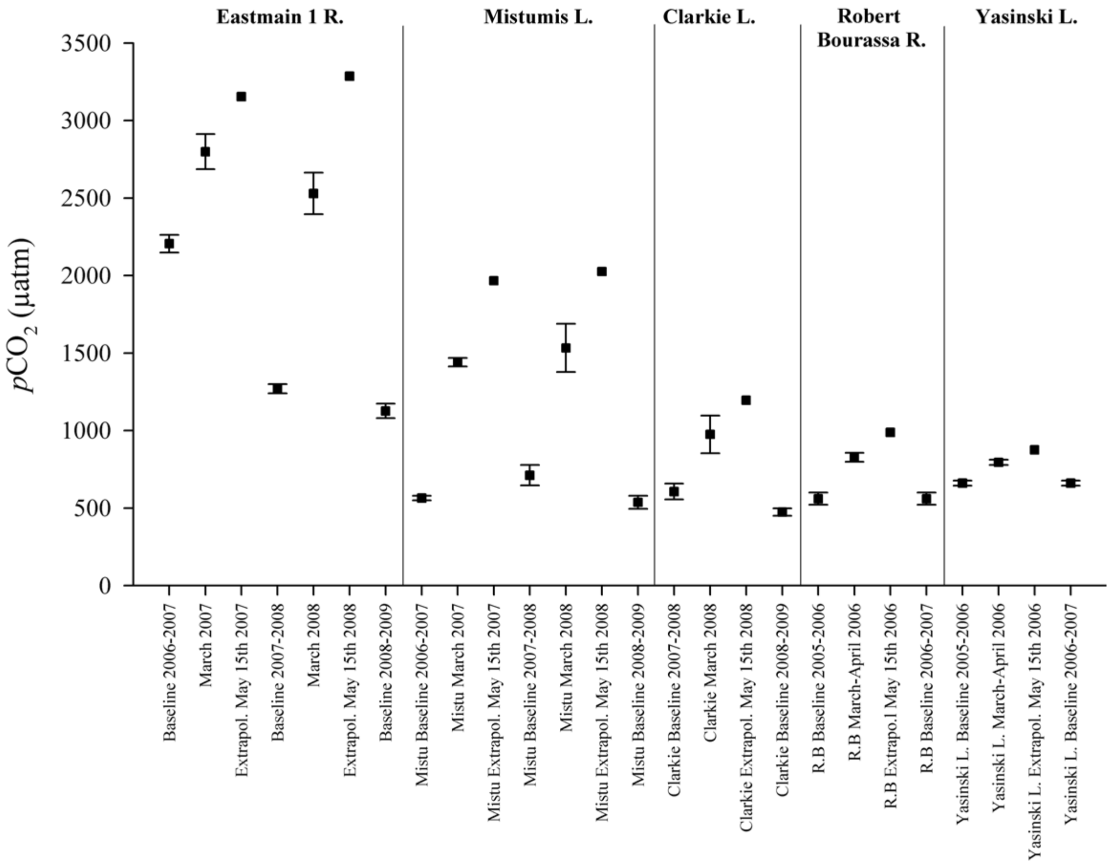

Fig. 3. Measured and extrapolated CO_2 partial pressure for the different studied systems. Bars represent standard errors.

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