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Variations in pCO_2 during summer in the surface water of an unproductive lake in northern Sweden

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ABSTRACT

Unproductive lakes are generally supersaturated with carbon dioxide (CO_2) and emit CO_2 to the atmosphere continuously during ice-free periods. However, temporal variation of the partial pressure of CO_2 (pCO_2) and thus of CO_2 evasion to atmosphere is poorly documented. We therefore carried out temporally high-resolution (every 6 h) measurements of the pCO_2 using an automated logger system in the surface water of a subarctic, unproductive, lake in the birch forest belt. The study period was June–September 2004. We found that the pCO_2 showed large seasonal variation, but low daily variation. The seasonal variation was likely mainly caused by variations in input and mineralization of allochthonous organic matter. Stratification depth probably also influenced pCO_2 of the surface water by controlling the volume in which mineralization of dissolved organic carbon (DOC) occurred. In lakes, with large variations in pCO_2, as in our study lake a high (weekly) sampling intensity is recommended for obtaining accurate estimates of the evasion of CO_2.

1. Introduction

Unproductive lakes are recognized as net heterotrophic and sources of carbon dioxide (CO_2) to the atmosphere, also on a global scale (e.g. Cole et al., 1994; Duarte and Prarie, 2005).

Supersaturation of CO_2 in lakes may have various sources, such as external inflow of supersaturated surface water and/or ground water (Kling et al., 1992), or internal CO_2 production by mineralization of organic matter in the sediments and in the water column (del Giorgio and Peters, 1994; Jonsson et al., 2001; Karlsson et al., 2007). The partial pressure of CO_2 (pCO_2) in the surface water of unproductive lakes is correlated to the concentration of dissolved organic carbon (DOC) of allochthonous origin (Hope et al., 1996; Sobek et al., 2005). Such connections have been found in boreal lakes (Sobek et al., 2003) but also in subarctic clear water lakes (Jonsson et al., 2003) with low concentrations of DOC. These results indicate the important role of DOC mineralization as a source of CO_2. Approximately 85% of the net production of CO_2 in the lake came from mineralization of allochthonous organic carbon in the water column, and only 15% via benthic mineralization (Åberg et al., 2007). Other studies show similar results (Algesten et al., 2005; Pace and Prairie, 2005).

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Most conclusions about the net heterotrophic character of lakes are based on analyses of samples collected with long-time intervals, often only a few times during a summer period.

There are only a few studies on the daily variation of pCO_2 in the surface waters of lakes. Those studies (Sellers et al., 1995; Maberly, 1996) show on large daily variations, mostly associated with variations in the relation between in-lake primary and secondary production. However, since the studies were performed in lakes with a high primary production, the knowledge of detailed temporal pCO_2 dynamics of unproductive lakes is still poor, and their possible effect on estimates of emission of CO_2 and the degree of net heterotrophy is not clear.

We therefore carried out a study with temporally high-resolution measurements of the surface water CO_2 in an unproductive lake. We use the results to discuss possible reasons for observed variations, and how seasonal variations affect estimates of net CO_2 emission from lakes to atmosphere. The study was made in Lake Diktar-Erik in northern Sweden in summer 2004. We also used data from samplings carried out in 2002 and 2003.

2. Methods

2.1. Study area

Lake Diktar-Erik, 15 km west of Abisko (18°49′E, 68°21′N) in northern Sweden, has an area of 8.8 ha, and mean and max depths of 5 and 17 m, respectively. The lake is unproductive, with

concentrations of total phosphorous and nitrogen of approximately 6 and 200 μg L^{-1}, respectively (Karlsson et al., 2002). The lake has one major inlet. For a further description of the catchment see Jonsson et al. (2007). The ice-free period during 2004 lasted from June 6 to October 17.

2.2. Hydrology

Discharge in the inlet and outlet was monitored using data loggers and pressure probes (Campbell Scientific Ltd.) calibrated against discharge measurements.

2.3. DOC concentrations

DOC was sampled 24 times in the lake inlet, between May 5 and October 19, 2004, using a Ruttner sampler. Samples were taken approximately once a week and more often during high discharge events. Water was filtered through pre-ignited (500 °C, 3 h) GF/F filters and acidified with 100 μL 1.2 M HCl per 10 mL water sample. DOC was analysed on a Schimadzu 5000 TOC analyser.

2.4. DIC concentrations

Water for analysis of dissolved inorganic carbon (DIC) and pCO_2 of the inlet was collected 26 times during the ice-free periods of 2002 and 2003 using a Ruttner sampler. Samples were taken approximately once a week or every second week. In 2004 samples for DIC analyses were taken on eight occasions in the inlet and on nine occasions in the outlet. On four occasions in 2004 eight samples were collected at a central point in the lake from 0, 1, 2, 3, 4, 5, 8 and 15 m depths using a Ruttner sampler. DIC and CO_2 concentrations were obtained using a headspace technique and CO_2 analysis was performed using an infra red gas analyser (IRGA) EGM-3 or an EGM-4 (PP-systems) as described in Jonsson et al. (2003).

2.5. Surface water pCO_2 measurements

A logger system, used for measurements of pCO_2 and surface water temperature, was placed on a raft at a central point of the lake between June 14 and September 21, 2004. The water temperature was logged every 10 min. A LiCor Li-820 infrared gas analyser (IRGA) measured the atmospheric air pressure (P) and the CO_2 concentration in both air and water. Two silicon membranes were connected to the IRGA via two plastic tube systems, and the volume of gas contained in the tube system was pumped around in each of the closed systems. The logger registered the CO_2 concentration and air pressure every 10 min. A set of magnetic valves, controlled by the logger, shifted the gas flow into the IRGA every 3 h to either come from the air or from the water tube systems. During the 3-h period the CO_2 concentration in the tube system equilibrated with the CO_2 concentration in the media (air or water) to reach stable values.

The raw pCO_2 values obtained from the logger system needed correction with the temperature dependent factor *km.* This factor was determined in a laboratory test by placing the silicon membrane tube system connected to the IRGA, and a thermistor, in a large water tank (the thermistor was placed just below the water surface); simultaneously we made triplicate measurements of the pCO_2 in the water using a standard headspace technique as described in Jonsson et al. (2003). CO_2 of the headspace gas was measured using an EGM-4 IRGA (PP-systems) with an internal H_2O compensating system. 18 separate measurements were made by varying the water temperature in the large tank between 5.1 and 26.4 °C. From these data a highly significant relationship between the water temperature and the ratio (*km*) between the pCO_2 of the water and the uncalibrated pCO_2 of the logger system (pCO_2 uncalib) was obtained. This ratio (*km*) was dependent on the water temperature:

$$km = 1.954 - 0.0340\,[\text{temp}] \quad (r^2 = 0.96,\ n = 18,\ F = 373). \tag{1}$$

The temperature corrected pCO_2 from the logger measurements was then calculated as:

$$pCO_2 = pCO_2 \text{ uncalib} \times km. \tag{2}$$

2.6. Calculation of the emission of CO_2 to the atmosphere

From our measurements of the surface water CO_2 concentration we estimated the emission of CO_2 by applying a gas transfer velocity (k). The k_{600} was modelled using the formula given by Cole and Caraco (1998).

$$k_{600} = 2.07 + 0.215U_{10}^{1.7}, \tag{3}$$

where k_{600} is gas transfer velocity at 20 °C in cm h^{-1} and U_{10} is wind speed at 10 m height.

The k_{600} was recalculated to the actual temperature in the surface water, using the Schmidt number at the measured water temperature as described in Wannikhof (1992). From the estimated k and the measured supersaturation of CO_2 in the surface water we could estimate the emission (Cole and Caraco, 1998).

$$F_{CO_2} = k\,(CO_{2water} - CO_{2equ}), \tag{4}$$

where F_{CO2} is exchange of CO_2 between air and water, CO_{2water} is measured concentration in the surface water and CO_{2equ} is air–water equilibrium concentration.

We used the measured seasonal average pCO_2 of the air to calculate the supersaturation of CO_2. We had measurements of the pCO_2 from 71 of the 100-d long period. Data from 29 d were missing due to power failure of the system, and daily pCO_2

values were obtained by interpolating between measurements. Wind data from 10 m heights were obtained from the Abisko Scientific Research Station, located 15 km east of the lake.

2.7. Sensitivity analysis

To calculate an uncertainty on the seasonal mean pCO_2 and mean emission of CO_2 created by different sampling frequencies (once each week, once every second week and once each month), data were collected from a data base containing daily values of pCO_2 and F_{CO_2}. For each sampling frequency, 12 000 randomly selected samples formed a population, which was used for obtaining uncertainty estimates. We used the 95% confidence intervals of the distributions as a measure of the uncertainty obtained due to sampling frequency, and compared these uncertainties with the measured seasonal logger mean of pCO_2 and F_{CO2}. The large population sizes ensured small differences between the mean and median (see Table 2) of the probability distributions (thus obtained normal distribution), and only small differences between the population means and the logger mean.

3. Results

The discharge was high during snow melt in spring and low during summer, and there was a high peak in late July caused by an extremely intensive rainfall (Fig. 1). During this extreme rain event the DOC concentration in the inlet stream increased to a maximum of 7.6 mg DOC L^{-1} (Fig. 1), and the DIC concentration in the inlet stream water decreased while the DIC concentration in the outlet water was rather stable. The average DOC concentration in the inlet stream during the ice-free period was 6.0 mg L^{-1}. The average theoretical water residence time during the ice-free period in the lake was 30 d.

The lake was constantly supersaturated with CO_2 compared to the atmospheric equilibrium concentration (Fig. 2), with a seasonal average pCO_2 of 725 μatm ($\pm$130 μatm, $\pm$1 *SD*, n = 160) in the water and 369 μatm ($\pm$9 μatm, $\pm$1 *SD*, n = 160) in the air. The minimum and maximum pCO_2 in the surface water were 571 and 1093 μatm, respectively. There were only small variations in the daily pCO_2, with a seasonal average daily coefficient of variation (CV) of 3%. The largest daily CV was 12%.

Periods with stable pCO_2 of the surface water (Fig. 2) were found in June (586 $\pm$ 8 μatm, average $\pm$1 *SD*) and during a large part of August (801 $\pm$ 30 μatm, average $\pm$1 *SD*). In both these periods there was an increased epilimnion depth and a low discharge (Fig. 2). As shown in Table 1 deeper water held higher concentrations of DIC during summer that could contribute with CO_2 to the surface water. We have no measurements of the CO_2 concentrations of deep water from this season, but data from previous summers showed on a pCO_2 over 3000 μatm at 15 m water depth (Jonsson, unpublished 2002).

There were three situations with a clear increase in the pCO_2, two in July, and one situation in early September. All three situations coincided with increasing discharge in the inlet stream (Fig. 2), and with an increased DOC concentration in the inlet stream (Fig. 1). In September this increase also coincided with a complete mixing of the water column (Fig. 2). In late July the pCO_2 increased from 604 μatm to a maximum of 1093 μatm. This maximum pCO_2 occurred on the falling limb of the extreme peak discharge (Fig. 2). During this discharge event the epilimnion volume was completely exchanged with water from the inlet stream.

The pCO_2 of the inlet stream water sampled during the ice-free period of 2002 and 2003 showed on a weak but significant negative relationship (r^2 = 0.17, P = 0.039, n = 26) with the

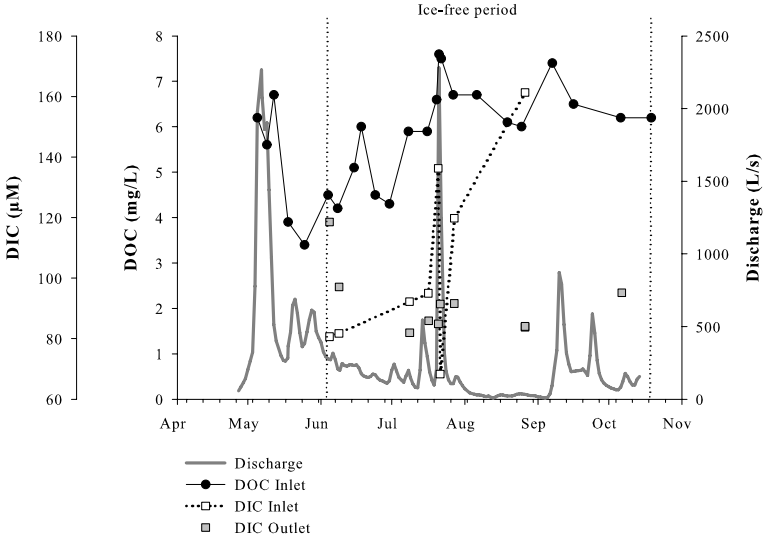

Fig. 1. Discharge and DOC concentration in the inlet stream of Lake Diktar-Erik during 2004. Included are also the concentrations of DIC in the inlet and the outlet streams. The ice-free period in the lake is indicated by the vertical, dotted, lines.

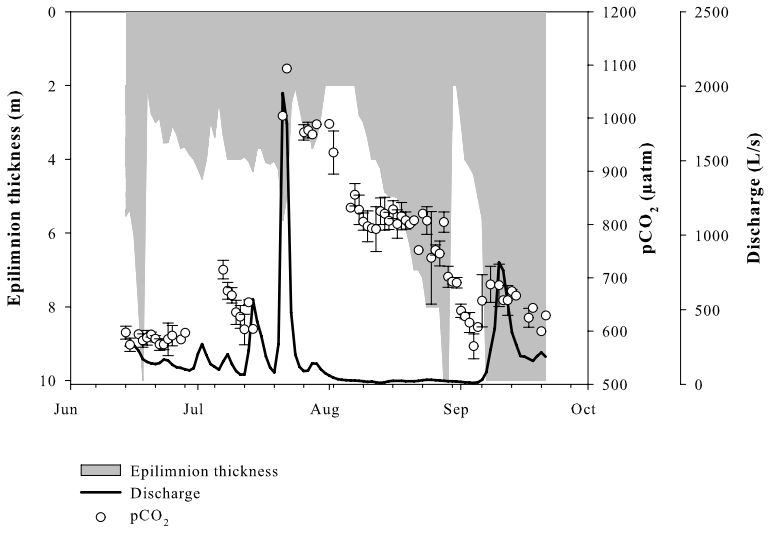

Fig. 2. Daily average pCO_2 (±1 *SD*) in the surface water, recorded with the logger system, and the epilimnion thickness, and the discharge in the inlet stream.

Table 1. The concentration of dissolved inorganic carbon (DIC) at different water depths in Lake Diktar-Erik during 2004

	DIC (μM)			
Depth (m)	June 18	July 19	August 20	September 17
0	99	93	95	103
1	92	93	99	105
2	93	97	101	105
3	93	100	98	103
4	92	104	98	100
5	92	108	113	107
8	126	122	181	97
15	131	126	207	105

discharge (Fig. 3a). The average pCO_2 in the inlet stream water during these periods was 653 ± 117 μatm (average ±1 *SD*), with the highest pCO_2 (926 μatm in 2002) measured during low discharge (8 L s^{-1}). The two points in Fig. 3a which represent the pCO_2 of the lake during the high flow event show that that the lake pCO_2 was much higher than what could be expected from the discharge—pCO_2 relationship, that is, these high concentrations do not seem to be a result of input of CO_2 rich water. During the same period there was also a strong negative relationship (r^2 = 0.78, $P < 0.001$, $n = 26$) between the DIC concentration and discharge (Fig. 3b). DIC concentrations in the inlet in 2004 fit well into this relationship, showing—in contrast to DOC—that the inorganic carbon content of the inlet stream water was diluted at higher discharge.

The emission of CO_2 to the atmosphere for the period June 14–September 21 was estimated to an average of 178 mg C m^{-2} d^{-1}. The minimum and maximum daily mean emission were estimated to 53 and 504 mg C m^{-2} d^{-1}, respectively. Depending on how often samples are taken a more or less representative estimate of the emission will be obtained (Table 2). Thus, the

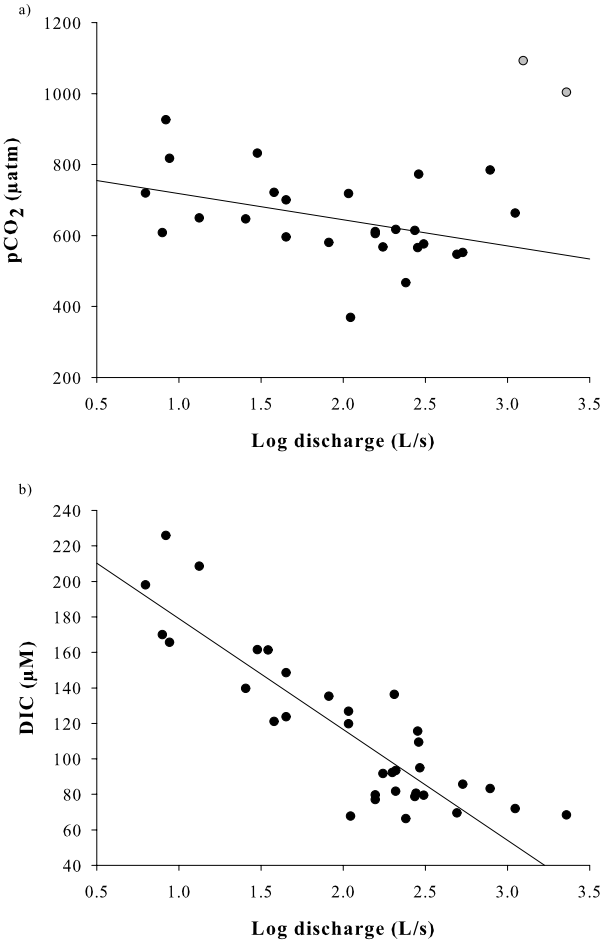

Fig. 3. (a) The pCO_2 of the inlet stream water in 2002 and 2003 versus the discharge (black circles). Grey circles show the pCO_2 of the lake water during the high flow event in July 2004 versus the discharge. (b) The DIC of the inlet stream water versus the discharge using data from 2002, 2003 and 2004.

Table 2. The effect of different sampling frequencies on calculations of the seasonal mean pCO_2 and mean emission of CO_2 from the lake to the atmosphere (F_{CO_2}). Results are presented as probability distributions using the 95% confidence intervals (CI). Included are the estimated seasonal median and mean (±1 *SD*) from the 12 000 random samplings

Sampling frequency	pCO_2			
	95% CI (μatm)	95% CI (% of logger mean)	Median (μatm)	Mean (μatm)
Monthly	617–822	84–111	737	737 (±41)
Every second week	687–792	93–107	741	740 (±29)
Weekly	722–759	98–103	740	740 (±10)
Logger (every 6 h)				737
	F_{CO_2}			
	95% CI (mg C m^{-2} d^{-1})	95% CI (% of logger mean)	Median (mg C m^{-2} d^{-1})	Mean (mg C m^{-2} d^{-1})
Monthly	112–277	63–156	170	177 (±43)
Every second week	125–240	70–135	176	178 (±30)
Weekly	149–211	84–118	177	178 (±16)
Logger (every 6 h)				178

confidence interval (CI) was considerably larger for low than for high sampling frequency. The sensitivity analysis also showed that the seasonal mean pCO_2 deviated less from logger mean than the emission of CO_2 at the same sampling frequency (Table 2).

4. Discussion

The low daily variation in the surface water pCO_2 contrasts to the large daily variations observed in productive lakes (Sellers et al., 1995; Maberly, 1996) and streams (Finlay, 2003), but is consistent with results from unproductive streams (Finlay, 2003). Low primary production, which cannot contribute to variations in CO_2 in Lake Diktar-Erik (Karlsson et al., 2001) explains the absence of daily variation. There was, however, a considerable seasonal variation in Lake Diktar-Erik (Fig. 2).

Increases of the surface water pCO_2 were seen in connection to increasing discharge in the inlet stream (Fig. 2). After the extreme pCO_2 increase in late July, the pCO_2 declined only slowly and did not reach typical, low discharge, values until 1 month after the peak. Smaller pCO_2 peaks occurred in connection to moderate discharge peaks in July and September. The connection between high pCO_2 and high flow could have been the result of increased input of CO_2 with the inlet water, or an increased mineralization of organic matter in the lake. Groundwater input has previously been shown to be negligible compared to surface water input in Lake Diktar-Erik (Åberg et al., 2005). The peak values in the lake during 2004 were much higher than what could have been expected as a result of input of supersaturated water via the inlet, and the data do not fit in the relationship between the pCO_2 and discharge in the inlet stream using data from summers 2002 and 2003 (Fig. 3a). There was also a strong negative relationship between the concentration of DIC and discharge using these data (Fig. 3b), with measured concentrations from 2004 fitting well into the relationship. The concentration of inorganic carbon in the inlet water thus decreased as discharge increased and input via inlet water was therefore probably not the source of the high pCO_2 (1093 μatm) measured in the lake during the high discharge event. Similar negative relationships between discharge and the concentration of CO_2 and HCO_3^- and CO_3^{2-} were also found by Finlay (2003) in streams in northern California, USA and by Dawson et al. (2002) in the Brocky Burn stream water in northeastern Scotland. We, therefore, do not have any data or arguments that supports the possibility that external input of CO_2 supply high CO_2 concentrations in the lake during high flow situations.

In contrast to decreasing DIC concentration there was a large input of DOC-rich water during the extreme rain event (Fig. 1). Not only the concentration and supply of DOC increased but probably also the availability. In an earlier study in Lake Diktar-Erik Jonsson et al. (2007) found increased concentrations of simple, readily available, organic substances as dissolved free amino acids and carbohydrates in connection to high discharge events. Similarly, Stepanauskas et al. (2000) found increased bioavailability of dissolved organic nitrogen during the spring flood in two boreal streams. Therefore, high discharge could contribute to high mineralization rates in the lake due to increased supply of DOC and increased supply of DOC with a high bioavailability. Observations of high rates of heterotrophic bacterial production in connection to high discharge were also observed by Bergström and Jansson (2000) in humic Lake Örträsket, in northern Sweden. Spot measurements of the net production of DIC using in situ incubations of water in the upper water column (0–5m depth) of Lake Diktar-Erik during summer 2004 varied between 9 and 157 μg C L^{-1} d^{-1} (Åberg et al., 2007). The pCO_2 measured in the lake surface water on July 21 corresponded to an increase in DIC

supply compared to the pre-event conditions of approximately 250 μg C L^{-1} d^{-1} (using the pre-event concentration of CO_2 from July 14 which was 27 μM, and assuming this was the concentration of the lake surface water on July 20). Thus, if mineralization alone should explain all of the increase in lake surface water pCO_2 during the high flow event the mineralization rate should have been approximately 250 μg C L^{-1} d^{-1}. This rate is within credible limits and comparable to dark respiration within the epilimnion for lakes with varying humic content (3.9–19.4 mg DOC L^{-1}) in southern Sweden, and less than the photorespiration in the surface water of several of these lakes (Granéli et al., 1996). Pace and Prairie (2005) reported a maximum mineralization rate of approximately 360 μg C L^{-1} d^{-1} in the oligotrophic Paul Lake (Michigan, USA), that was considerably higher than the average of approximately 100 μg C L^{-1} d^{-1}.

Even though we are not able to present direct evidence, the data presented here and in other studies in Lake Diktar-Erik (Åberg et al., 2005, 2007; Karlsson et al., 2007) does imply that mineralization of allochthonous organic matter was a more important factor controlling surface water pCO_2, than external inflow of CO_2. We, therefore, suggest that episodic increases of the surface water pCO_2 were mainly controlled by episodic increases of the mineralization of allochthonous organic carbon.

Evasion in combination with decreasing mineralization rates were probably the main reasons to the decline in pCO_2 during the low discharge period in August (Fig. 2). This decline was interrupted by a period with stable pCO_2, which occurred during a period when the epilimnion became thicker (Fig. 2). Therefore, DIC rich water (Table 1) from greater depths was introduced in the epilimnion and DOC mineralization in a larger volume of water contributed to the surface water pCO_2 (see e.g. Riera et al., 1999). Possibly, contribution of CO_2 from both processes was the reason to the stabilization of pCO_2 during this period.

The low supersaturation observed in September (Fig. 2) was probably en effect of low mineralization of DOC observed in Lake Diktar-Erik during autumn (Åberg et al., 2007).

The emission of CO_2 to the atmosphere during the study period (mean 178 mg C m^{-2} d^{-1}) was higher than previous estimates from the lake of 70 mg C m^{-2} d^{-1} (Jonsson et al., 2003) and 113 mg C m^{-2} d^{-1} (Åberg et al., 2005). These estimates were made for other years, with other environmental conditions, and can therefore be expected to differ. For example, none of the other seasons had a high flow event like that in 2004, and probably not such large variations in pCO_2 as found here. However, from the sensitivity test (Table 2) it is obvious that uncertainties caused by sampling frequencies vary considerably more for the estimated seasonal mean emission compared to the seasonal mean pCO_2. It is therefore important to have a high sampling frequency of the pCO_2 and especially of the gas transfer velocity (k) to obtain accurate estimates of the emission. The gas transfer velocity was here modelled from wind speed according to Cole and Caraco (1998). This model was obtained using data from low-wind conditions, and wind speed only explained approximately 60% of the variation of the k in their data. Therefore, estimates of CO_2 emission should be used with care where the sampling frequency is low. We propose that a too sparse sampling frequency could lead to uncertain estimates of the emission of CO_2 to the atmosphere, and that it is especially important to have good estimates/measurements of the gas transfer velocity.

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