

## Temporal and spatial carbon dioxide concentration patterns in a small boreal lake in relation to ice-cover dynamics

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Global carbon dioxide (CO<sub>2</sub>) emission estimates from inland waters commonly neglect the ice-cover season. To account for CO<sub>2</sub> accumulation below ice and consequent emissions into the atmosphere at ice-melt we combined automatically-monitored and manually-sampled spatially-distributed CO<sub>2</sub> concentration measurements from a small boreal ice-covered lake in Sweden. In early winter, CO<sub>2</sub> accumulated continuously below ice, whereas, in late winter, CO<sub>2</sub> concentrations remained rather constant. At ice-melt, two CO<sub>2</sub> concentration peaks were recorded, the first one reflecting lateral CO<sub>2</sub> transport within the upper water column, and the second one reflecting vertical CO<sub>2</sub> transport from bottom waters. We estimated that 66%–85% of the total CO<sub>2</sub> accumulated in the water below ice left the lake at ice-melt, while the remainder was stored in bottom waters. Our results imply that CO<sub>2</sub> accumulation under ice and emissions at ice-melt are more dynamic than previously reported, and thus need to be more accurately integrated into annual CO<sub>2</sub> emission estimates from inland waters.

### Introduction

Inland waters play an important role in the global carbon cycle, receiving, transporting and processing carbon and emitting carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) into the atmosphere (Battin *et al.* 2009). Several global CO<sub>2</sub> emission estimates from lakes and streams are available (Cole *et al.* 2007, Tranvik *et al.* 2009, Aufdenkampe *et al.* 2011) with temporal, in particular seasonal variations, based on simple assumptions rather than evidence. Most of the lakes in the northern hemisphere are however covered by ice during substantial parts of the year (Weyhen-

meyer *et al.* 2011) where ice acts as a barrier to atmospheric exchange causing high concentrations of CO<sub>2</sub> to accumulate in lakes (Striegl and Michmerhuizen 1998, Kortelainen *et al.* 2006). Most commonly global lake CO<sub>2</sub> emission estimates compensate for CO<sub>2</sub> accumulation (i.e. the lack of CO<sub>2</sub> emitted) during the ice-cover period by assuming that a rapid outburst of CO<sub>2</sub> to the atmosphere at ice-melt accounts for all the CO<sub>2</sub> that has accumulated during winter (Cole *et al.* 2007). More recently, Butman and Raymond (2011) attempted to account for the ice-cover period of running waters by calculating annual CO<sub>2</sub> emissions for the open-water season only.

Raymond *et al.* (2013) offered another approach in the currently most comprehensive estimate of CO<sub>2</sub> emissions from global inland waters. They discounted periods during which running waters were ice-covered from the emission calculations, while they assumed linear accumulation of CO<sub>2</sub> under the ice followed by complete and rapid emission at ice-out for lakes and reservoirs (Raymond *et al.* 2013). However, all these methods neglect the dynamics and importance of under ice CO<sub>2</sub> accumulation and CO<sub>2</sub> outburst at spring ice-melt, which in lakes can be substantial: Karlsson *et al.* (2013), for example, estimated that up to 56% of the total annual CO<sub>2</sub> emission can occur at ice-melt alone. Such estimates are, however, based on manual samples that do not capture CO<sub>2</sub> dynamics at an hourly and daily time scales. Since CO<sub>2</sub> emission at ice-melt can occur within days (Huotari *et al.* 2009), improved estimates of CO<sub>2</sub> emissions during this period are needed.

It is well established that lakes are supersaturated with CO<sub>2</sub> caused by net heterotrophy, where respiration exceeds primary production (Cole *et al.* 1994). Moreover, high CO<sub>2</sub> accumulation in lakes under ice has been attributed to respiration of terrestrial organic-carbon inputs (Striegl *et al.* 2001) and of organic carbon produced by benthic algae the previous summer (Karlsson *et al.* 2008). In addition to respiration, variations in lake water CO<sub>2</sub> are a result of photosynthesis, photo-transformation, methane oxidation, catchment contribution and water column mixing. To some extent, ice and snow-cover dynamics alter these processes, preventing atmospheric inputs and gas exchange (Striegl *et al.* 2001), limiting solar radiation (Belzile *et al.* 2001), and reducing the effect of turbulent heat flux on lake mixing (Rouse *et al.* 2005). Thus, the seasonal dynamics of snow and ice cover greatly influences the magnitude of these mechanisms (Gunn and Keller 1985), which consequently may lead to spatial and temporal variations in lake water CO<sub>2</sub> during the ice-cover period.

One way to improve estimates of CO<sub>2</sub> emissions is to increase the frequency of CO<sub>2</sub> measurements (Sellers *et al.* 1995). Recent advancements in technology have allowed for the development of *in situ* CO<sub>2</sub> sensors (e.g. Johnson *et al.* 2010). However, at present, only a very limited number of *in situ* continuous CO<sub>2</sub> measurements

under ice and at ice-melt are available for lakes and reservoirs (Baehr and DeGrandpre 2002, 2004, Huotari *et al.* 2009, Demarty *et al.* 2011). These studies highlight the complexity of CO<sub>2</sub> dynamics at ice-melt but are limited in their ability to account for the spatial variability of CO<sub>2</sub> across the entire lake or reservoir basin. A recent study by Schilder *et al.* (2013) suggests that surface water CO<sub>2</sub> concentrations during the open-water period can vary across the lake. Additionally, CO<sub>2</sub> concentrations can vary vertically in the lake during stratification periods, with CO<sub>2</sub>-rich bottom waters contributing to high CO<sub>2</sub> emission during turnover periods (Kortelainen *et al.* 2006). Thus, in order to improve the accuracy of CO<sub>2</sub> emission estimates, during the understudied ice-melt period, continuous CO<sub>2</sub> concentration measurements should be combined with spatially distributed CO<sub>2</sub> concentration measurements in ice-covered lakes.

This study aimed to explore the current assumptions global CO<sub>2</sub> emission estimates make for ice-covered lakes, i.e. that CO<sub>2</sub> accumulates linearly under ice and that at ice-melt all CO<sub>2</sub> that has been accumulated is rapidly emitted into the atmosphere. Further, we aimed to quantify the spatial and temporal variability of CO<sub>2</sub> in lake water from ice-on to ice-off. We hypothesized that (1) CO<sub>2</sub> accumulates linearly under ice during the whole winter, (2) CO<sub>2</sub> accumulates faster in bottom than in surface waters, and finally (3) the amount of CO<sub>2</sub> that is emitted to the atmosphere at ice-melt is comparable to the amount of CO<sub>2</sub> that has been accumulated during the winter.

## Methods

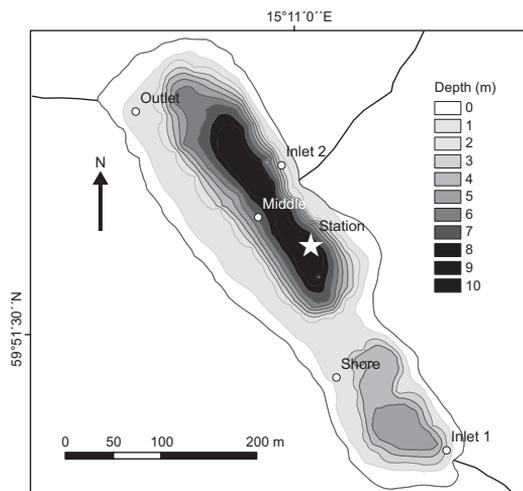
### Study area

To test our hypotheses we sampled Lake Gäddtjärn, a small boreal lake (6.8 ha) located in mid-Sweden (59.86°N, 15.18°E) with a maximum depth of 10 m, mean depth of 3.8 m, and a volume of 260 000 m<sup>3</sup> at an altitude of 254 m a.s.l. The lake has two main inlets, which drain a catchment area of 226 ha comprising 84% boreal forest, 12% wetlands and 4% water (draining three very small headwater lakes). About 20%

of the total catchment area drains directly into the lake, while 80% drains via two streams (Kokic *et al.* 2015). The lake has a theoretical water residence time of ~2 months (calculated as mean discharge at the outlet divided by the lake volume) and drains into a larger lake further downstream. According to the Swedish Meteorological and Hydrological Institute, the long-term mean (1961–1990) annual temperature is 4.5 °C and annual precipitation is 900 mm. Ice formation usually begins in mid-November to early December and ice-melts in mid-April. Six sampling sites on the lake were chosen to represent varying lake depths from 1.4 to 9.5 m (Fig. 1).

### Continuous measurements

We automatically monitored CO<sub>2</sub> concentration ( $\mu\text{M}$ ), dissolved oxygen (DO,  $\text{mg l}^{-1}$ ), pH, water temperature (°C) and light intensity (lux) above the deepest basin of the lake (depth of 9.5 m), during the ice-cover and ice-melt periods between 22 Jan. and 7 May 2013. Hourly partial pressure of CO<sub>2</sub> ( $p_{\text{CO}_2}$ ) was measured (and converted into CO<sub>2</sub> concentration) using the Submersible Autonomous Moored Instrument for CO<sub>2</sub> (Sunburst Sensors, SAMI2) suspended in the water column at 2 m depth. SAMI2 was factory calibrated towards NIST (National Institute of Standards and Technology) traceable NDIR (Nondispersive Infrared Sensor) and has an accuracy of  $\pm 3 \mu\text{atm}$  and precision  $< 1 \mu\text{atm}$ . We applied correction factors supplied by sunburst sensors when calculating CO<sub>2</sub> concentration, since our CO<sub>2</sub> measurements (mean 2800  $\mu\text{atm}$ ) surpassed the NIST-approved validity range of calibration (300–1300  $\mu\text{atm}$ ). DO and pH were measured hourly with an autonomous sonde (YSI, Model 6600V2-03; ROX DO probe, Model 6450 AF) suspended at 4 m depth (deployed as part of a separate project). Light intensity was measured hourly with a pendant light logger (HOBO, Model UA-002-64) attached to the top of a subsurface float placed 0.1 m below the surface water. Water temperature was recorded every 4 hours at every meter throughout the total depth of the water column (9 m) with temperature loggers (onset HOBO, Model Pro V2).



**Fig. 1.** Sampling locations in Lake Gäddtjärn. The star indicates the station site where CO<sub>2</sub> concentrations (shown in Fig. 2), dissolved oxygen, pH, water temperature and light intensity were monitored automatically and where the CO<sub>2</sub> vertical profile sampling was carried out.

### Manual measurements

In addition to automatic measurements, between 13 Dec. 2012 and 7 May 2013, we collected water samples five times during the ice-on and once at ice-off. Water was collected using a Ruttner water sampler from five surface-water sites (sampled at 0.5 m) and one vertical profile site (sampled at 0.5, 2, 4, 6 and 8 m depth) located at the deepest point of the lake (Fig. 1). Bubble-free water was drained from the Ruttner into a 60 ml polypropylene syringe and a 12 ml glass vial, for CO<sub>2</sub> and dissolved inorganic carbon (DIC) analyses, respectively. Additional water was collected for dissolved organic carbon (DOC) analysis. All water samples were stored dark and cool until analyzed. Further, at each location, temperature, DO and specific conductivity were measured using an HQ40d Portable Multi-parameter sonde (HACH). Upon returning from the field, water samples for DOC were filtered through a precombusted 0.7  $\mu\text{m}$  Whatman GF/F glass fiber filter. A total carbon analyzer (Sievers 900) equipped with a membrane-based conductivity detector was used to measure DOC and DIC. For each water sample, DOC and DIC were reported as means of three measurements

taken by the total carbon analyzer. DIC and DOC samples were analyzed within two and seven days of sampling, respectively. CO<sub>2</sub> measurements were made immediately upon returning from the field using the headspace equilibration technique, where 40 ml of water was replaced with ambient air and equilibrated with the lake water by vigorously shaking.  $p_{\text{CO}_2}$  of the extracted headspace gas phase and ambient air were measured with a portable infrared gas analyzer (IRGA) (EGM-4, PP Systems Inc, USA) which has an accuracy of < 1% of the calibration range (0–5000  $\mu\text{atm}$ ). Headspace  $p_{\text{CO}_2}$  was taken as the average of three measurements and CO<sub>2</sub> concentration was calculated according to Henry's law presented by Weiss (1974) correcting for temperature and the amount of CO<sub>2</sub> added to the syringe by the ambient air (e.g. Sobek *et al.* 2003, Demarty *et al.* 2011, Karlsson *et al.* 2013).

Using manually sampled CO<sub>2</sub> from the vertical profile site, i.e. above the deepest point of the lake, we quantified temporal changes in CO<sub>2</sub> concentrations ( $\Delta\text{CO}_2$ ,  $\mu\text{M d}^{-1}$ ) for 0.5 m (surface water) and at 8 m (bottom water). We received a rate of change by taking the CO<sub>2</sub> concentration difference between sampling occasions divided by the number of days between the sampling.  $\Delta\text{CO}_2$  was calculated for the early winter (13 Dec. 2012–4 Feb. 2013), late winter (4 Feb.–15 Apr.), and the ice-melt (15 Apr.–7 May) periods. We also estimated whole-lake CO<sub>2</sub> accumulation and loss rates ( $r$ , mol CO<sub>2</sub> d<sup>-1</sup>) by considering the whole-lake CO<sub>2</sub> storage (CS, mol CO<sub>2</sub>). CS was calculated as the sum of the measured CO<sub>2</sub> depth profile integrated with the volume of each corresponding depth layer (Michmerhuizen *et al.* 1996). Lake volume at each depth was obtained by digitizing lake contour maps for each 1 m depth. Whole-lake  $r$  was then calculated as:

$$r = \frac{\text{CS}_{t_2} - \text{CS}_{t_1}}{n}, \quad (1)$$

where CS is the whole-lake CO<sub>2</sub> storage at sampling time  $t$ , and  $n$  is the number of days between sampling occasions  $t_1$  and  $t_2$ . Positive values of  $r$  indicate CO<sub>2</sub> accumulation in the lake while negative ones CO<sub>2</sub> loss from the lake.

The relative amount of CO<sub>2</sub> accumulated under ice that was released during spring melt ( $C_{\text{release}}$ , %) was calculated as:

$$C_{\text{release}} = \frac{\text{CS}_L}{\text{CS}_A} = \frac{\text{CS}_{\text{last ice}} - \text{CS}_{\text{no ice}}}{\text{CS}_{\text{last ice}} - \text{CS}_{\text{first ice}}}, \quad (2)$$

where CS<sub>L</sub> is the amount of CO<sub>2</sub> leaving the lake during the ice-off season, CS<sub>A</sub> is the amount of CO<sub>2</sub> accumulated in the lake during the sampling period below the ice cover, CS<sub>first ice</sub> is the CS on 13 Dec., CS<sub>last ice</sub> is the CS on 11 Mar., and CS<sub>no ice</sub> is the CS on 7 May.

Since sampling began after the ice had been formed and we did not capture the exact time of ice-off we also made an estimate of  $C_{\text{release}}$  for the whole ice-cover period by accounting for the full duration of the ice cover. We assumed ice-on to occur on the lake after air temperatures below 0 °C persisted for four consecutive days, corresponding to 28 Nov. 2012. We further assumed ice-off to begin on 15 Apr. 2013, corresponding to a sudden and apparent increase in continuously-measured underwater light conditions. Thus, CS<sub>first ice</sub> was the CS on 28 Nov., calculated as the CS on 13 Dec. minus early winter whole-lake  $r$  (13 Dec. 2012–4 Feb. 2013) times 15 days (28 Nov. 2012–13 Dec. 2013). CS<sub>last ice</sub> was the CS on 15 Apr., calculated as the CS on 11 Mar. plus late winter whole-lake  $r$  (4 Feb.–15 Apr.) times 35 days (11 Mar.–15 Apr.).

## CO<sub>2</sub> emission at ice-melt

Continuous CO<sub>2</sub> concentrations were used to estimate CO<sub>2</sub> emission (CO<sub>2E</sub>, mmol m<sup>-2</sup> d<sup>-1</sup>) during ice-melt using the following equation:

$$\text{CO}_{2E} = k_{\text{CO}_2} \times (\text{CO}_{2w} - \text{CO}_{2a}), \quad (3)$$

where  $k_{\text{CO}_2}$  is the gas transfer velocity (cm h<sup>-1</sup>) and  $(\text{CO}_{2w} - \text{CO}_{2a})$  accounts for the difference between CO<sub>2</sub> concentrations in the water and in the air. CO<sub>2w</sub> was measured with the SAMI2 instrument at 2 m depth below the surface. CO<sub>2a</sub> was set to 406  $\mu\text{atm}$ , the average ambient atmospheric  $p_{\text{CO}_2}$  manually measured at the lake. To account for the difference between CO<sub>2</sub> concentrations just below the water surface we applied a correction factor of -19% to the continuous CO<sub>2</sub> concentration measurements made with the SAMI2 instrument at 2 m depth. This correction is based on the observed CO<sub>2</sub> concentration

difference between 0.5 m and 2 m during the ice-melt period (7 May). The correction results in lower CO<sub>2</sub> concentrations at the water–atmosphere interface, thus our CO<sub>2</sub> emission estimates are conservative.  $k_{\text{CO}_2}$  was estimated from  $k_{600}$  normalized to a temperature-dependent Schmidt number for CO<sub>2</sub> (600 at 20 °C) according to Jähne *et al.* (1987).  $k_{600}$  was derived from wind speed based on the relationship from Cole and Caraco (1998). Since the Cole and Caraco (1998) model was based on measurements from a small, wind-sheltered lake comparable to ours, it is well suited to estimate CO<sub>2</sub> emission for this study. Hourly wind speed data were acquired from the nearby meteorological station Klotten site A (59.52°N, 15.15°E). In addition, for validation purposes,  $k_{600}$  was also estimated using 6 floating chambers which were placed in the lake to measure  $k_{600}$  on 7 May 2013 (Krenz 2013). The floating chamber derived  $k_{600}$  for the lake ranged from 1.9 to 4.2 cm h<sup>-1</sup> with a median of 2.3 cm h<sup>-1</sup>, and the Cole and Caraco (1998) model for the same day corresponded to an estimated median  $k_{600}$  of 2.4 cm h<sup>-1</sup> and range from 2.1 to 3.1 cm h<sup>-1</sup>. Thus, the two  $k_{600}$  estimates agreed relatively well. To avoid overestimation of  $k_{600}$  at high wind speeds we set the wind speed derived  $k_{600}$  to a maximum threshold of 4.2 cm h<sup>-1</sup> since this was the maximum  $k_{600}$  directly measured with floating chambers; again, by doing so we calculate a conservative CO<sub>2</sub> emission estimate. The mean ± standard deviation (SD) were calculated for  $k_{600}$ , CO<sub>2</sub> and CO<sub>2E</sub>.

## Statistical analyses

To test whether CO<sub>2</sub> concentrations below the ice cover significantly increased or not we applied a Mann-Kendall trend test, based on the non-normally distributed daily mean CO<sub>2</sub> concentration data from the continuous measurements (Shapiro-Wilk's test result:  $p < 0.0001$ ,  $n = 84$ ). We considered an increase or decrease as significant at  $p < 0.05$ . We also used the Mann-Kendall trend test to quantify the rate of change in the CO<sub>2</sub> concentration below ice (in days) by calculating the Theil slopes for different periods.

To investigate whether CO<sub>2</sub> accumulates in the bottom water we compared the manually-

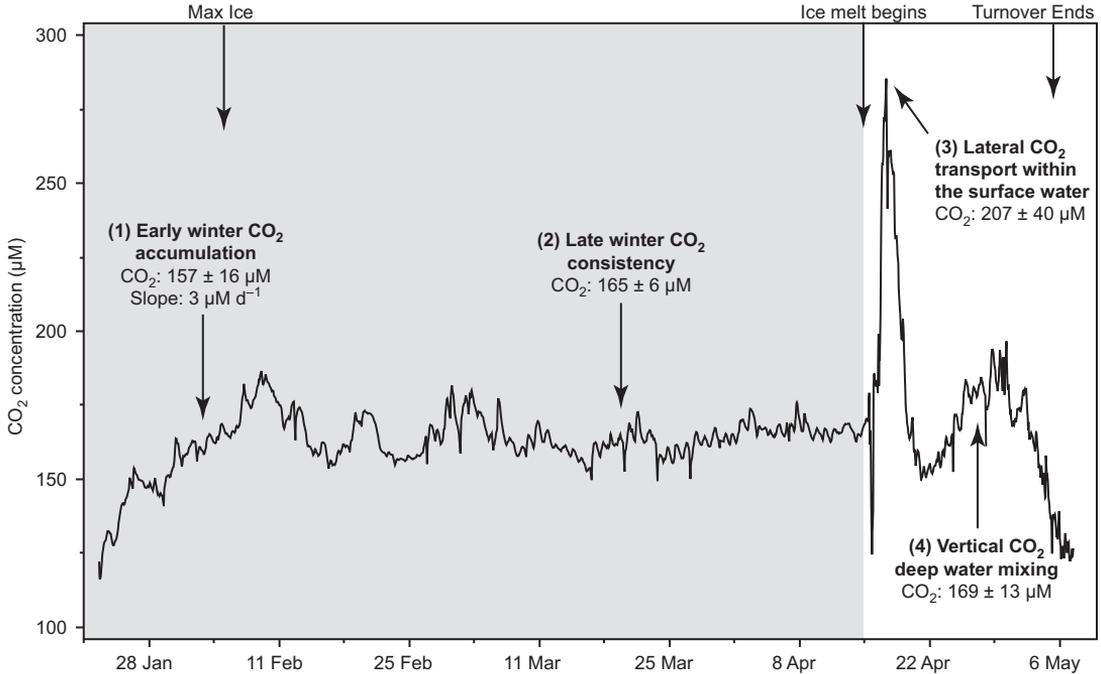
measured CO<sub>2</sub> concentrations from the bottom water (8 m water depth) at the continuous CO<sub>2</sub> measuring site (site Station in Fig. 1) with the ones from the surface water (0.5 m water depth). Surface and bottom water samples at this site were manually taken on six occasions (13 Dec., 22 Jan., 4 Feb., 26 Feb., 11 Mar. and 7 May). Since the CO<sub>2</sub> data in both the surface and bottom water were normally distributed (Shapiro-Wilk's test result:  $p > 0.05$ ,  $n = 6$  for both surface and bottom water) we applied a matched-pairs *t*-test where surface and bottom water CO<sub>2</sub> concentration was paired for each sampling occasion.

Finally, we tested whether there were horizontal CO<sub>2</sub> concentration differences in surface waters below the ice cover, i.e. from December to March. For the test we used a two-way analysis of variance (ANOVA) where we set site (six sites: Inlet1, Inlet 2, Middle, Outlet, Shore and Station) and time (five sampling occasions: 13 Dec. 2012, and 22 Jan., 4 Feb., 26 Feb. and 11 Mar. 2013) as the two independent variables and CO<sub>2</sub> concentration in surface waters at the six sites from December to March as the dependent variable. The CO<sub>2</sub> concentration in surface waters at the six sites from December to March was normally distributed (Shapiro-Wilk's test result:  $p > 0.05$ ,  $n = 30$ ). All statistical tests were performed in JMP version 11.0.0.

## Results

### Hourly surface-water CO<sub>2</sub> patterns

The surface-water (2 m depth) CO<sub>2</sub> concentration (continuous measurements) change comprised four distinct phases between ice-on and ice-off: an increase from 22 Jan. to 9 Feb., rather constant concentrations from 10 Feb. to 15 Apr., and two peaks after 15 Apr. (Fig. 2). During 22 Jan.–9 Feb., the ice cover steadily built up, and surface water CO<sub>2</sub> concentrations rapidly and significantly increased by 3 μM d<sup>-1</sup> (Mann-Kendall test:  $\tau = 3$ ,  $p < 0.01$ ,  $n = 19$ ). This increase continued until the ice reached its maximum thickness in early February (Table 1 and Fig. 2). Surface-water CO<sub>2</sub> concentration reached a maximum of 187 μM on 9 Feb. and plateaued thereafter until ice-melt began on



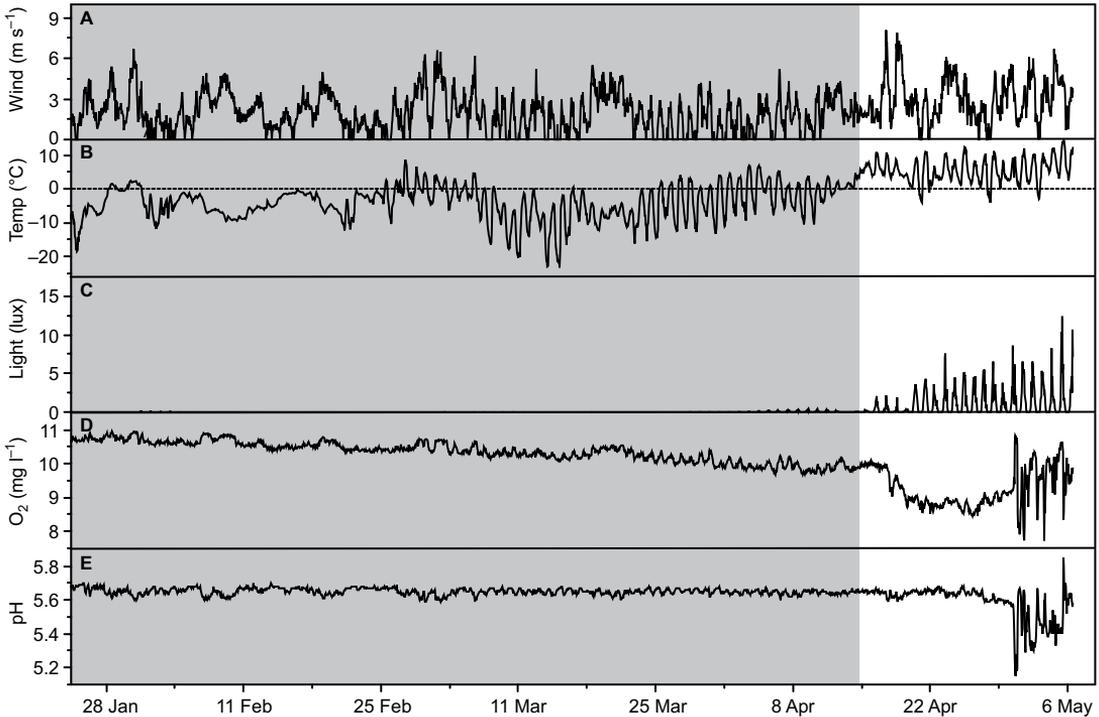
**Fig. 2.** Automatically-monitored hourly surface-water (2 m)  $\text{CO}_2$  concentrations measured during the ice-cover (grey) and ice-melt periods (white) above the deepest site (station site) in Lake Gäddtjärn between 22 Jan. and 7 May 2013.  $\text{CO}_2$  concentrations are reported as factory-corrected values. For each period mean  $\pm$  SD is reported. For the first, period the Theil slope indicating change over time is reported.

15 Apr. During this period (10 Feb.–15 Apr.), surface-water  $\text{CO}_2$  concentrations did not show a significant change (Mann-Kendall test:  $\tau = -0.008$ ,  $p = 0.85$ ,  $n = 65$ ). As ice-melt began (16 Apr.–20 Apr.), surface-water  $\text{CO}_2$  concentrations rapidly increased within only two days from  $179 \mu\text{M}$  to  $286 \mu\text{M}$  (on 17 Apr.), which corre-

sponded to an apparent increase in light intensity (Fig. 3C), and was followed by an equally rapid decline to  $157 \mu\text{M}$  within the next two days. This steep first  $\text{CO}_2$  concentration peak was followed by a more gradual  $\text{CO}_2$  concentration peak (21 Apr.–4 May) of  $197 \mu\text{M}$  on 30 Apr., followed by a decline to  $137 \mu\text{M}$  within four days (Fig. 2).

**Table 1.** Ice and snow conditions on the lake, water temperature and chemistry measured at spatially-sampled surface-water sites (Fig. 1,  $n = 6$ ). Mean  $\pm$  SD for each sampling date is reported. Whole-lake  $\text{CO}_2$  storage (CS) was estimated from integrating  $\text{CO}_2$  depth profiles (see Methods); m.d. = missing data, n.a. = not applicable.

	13 Dec.	22 Jan.	4 Feb.	26 Feb.	11 Mar.	7 May
Ice thickness (cm)	$16 \pm 2$	$27 \pm 8$	$46 \pm 14$	$35 \pm 4$	$46 \pm 13$	n.a.
Snow depth on ice (cm)	m.d.	m.d.	$4 \pm 1$	$14 \pm 3$	$17 \pm 2$	n.a.
Water temp ( $^{\circ}\text{C}$ )	$0.1 \pm 0$	$0.2 \pm 0.1$	$0.9 \pm 0.9$	$0.5 \pm 0.3$	$0.3 \pm 0.3$	$12 \pm 0.8$
Conductivity ( $\mu\text{S cm}^{-1}$ )	$11.7 \pm 5.8$	$19.6 \pm 5.3$	$20.8 \pm 4.4$	$21.4 \pm 0.7$	$21.8 \pm 0.6$	$17.7 \pm 0.2$
DO ( $\text{mg l}^{-1}$ )	m.d.	$13.2 \pm 0.0$	$12.2 \pm 1.0$	$12.4 \pm 0.4$	$12.4 \pm 0.8$	$9.9 \pm 0.1$
DOC ( $\text{mg l}^{-1}$ )	$14.3 \pm 0.6$	$12.2 \pm 1.1$	$12.2 \pm 0.8$	$11.9 \pm 1.2$	$11.2 \pm 0.5$	$12.0 \pm 0.1$
DIC ( $\text{mg l}^{-1}$ )	$1.1 \pm 0.1$	$1.5 \pm 0.2$	$1.8 \pm 0.3$	$1.9 \pm 0.2$	$2.3 \pm 0.3$	$1.4 \pm 0$
$\text{CO}_2$ ( $\mu\text{M}$ )	$102 \pm 10$	$145 \pm 27$	$183 \pm 30$	$162 \pm 22$	$189 \pm 24$	$113 \pm 8$
Whole-lake CS (mol)	27938	36116	45856	42844	45905	30618



**Fig. 3.** (A) Wind speed, (B) ambient temperature, (C) light intensity at the water surface, (D) dissolved oxygen, and (E) pH measured at 4 m depth during the ice-cover (grey) and ice-melt periods (white) between 22 Jan. and 7 May 2013. The dashed line in the ambient temperature panel represents 0 °C, the freezing point of water.

### CO<sub>2</sub> spatial variability from ice-on to ice-melt

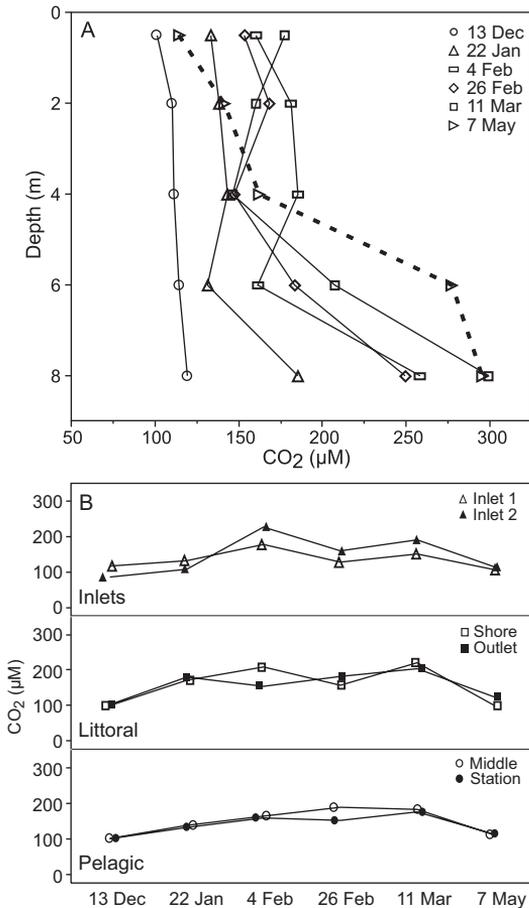
We found that the CO<sub>2</sub> concentrations in the surface and bottom waters (0.5 and 8 m, respectively) at the site with the continuous CO<sub>2</sub> measurements (site Station in Fig. 1) differed significantly (matched pairs *t*-test result:  $t = 4.1$ ,  $p < 0.01$ , number of pairs = 6). The largest difference between surface and bottom water CO<sub>2</sub> concentrations (181 μM) at that site occurred in May. The difference remained significant when we considered only the ice-cover period, i.e. five sampling occasions from 13 Dec. to 11 Mar. (matched pairs *t*-test result:  $t = 4.2$ ,  $p < 0.05$ , number of pairs = 5). We observed that the difference in the CO<sub>2</sub> concentrations between the surface and bottom waters at the site Station increased below the ice cover from 18 μM on 13 Dec. to 122 μM on 11 Mar. The increase was substantially faster during early winter with mean  $\Delta\text{CO}_2$  of 1.1 μM d<sup>-1</sup> in the surface water and 2.6 μM d<sup>-1</sup> in the bottom water as compared

with that during late winter when  $\Delta\text{CO}_2$  equaled 0.5 μM d<sup>-1</sup> in the surface water and 1.2 μM d<sup>-1</sup> in the bottom water. During the ice-melt period  $\Delta\text{CO}_2$  was 2.7 μM d<sup>-1</sup> in the surface water and 0.2 μM d<sup>-1</sup> in the bottom water.

Applying a two-way ANOVA to test the CO<sub>2</sub> concentration variability in the surface water across six sampling sites during the ice-cover period we found that time had a significant effect on the CO<sub>2</sub> variability while site had not ( $F = 7.0$ ,  $p < 0.0001$  for time and  $p > 0.05$  for site,  $n = 30$ ). Thus, the variation in the horizontal CO<sub>2</sub> concentration below the ice cover was insignificant in comparison with the temporal variation in the CO<sub>2</sub> concentration.

### Whole-lake CO<sub>2</sub> storage from ice-on to ice-melt

During the sampled ice-cover period (13 Dec. 2012–11 Mar. 2013), whole-lake CS increased by 61% from 27 938 mol to 45 905 mol (Table 1). Whole-lake CO<sub>2</sub> accumulation (Eq. 1) rap-



**Fig. 4.** (A) Vertical and (B) horizontal, surface-water CO<sub>2</sub> concentrations in Lake Gäddtjärn during the ice-cover period (13 Dec. 2012–11 Mar. 2013) and at ice-off (7 May 2013).

idly increased in early winter (13 Dec. 2012–4 Feb. 2013) with  $r = 338 \text{ mol d}^{-1}$ . Thereafter, from 4 Feb.–11 Mar., whole-lake CO<sub>2</sub> storage remained relatively stable until ice-melt ( $r = 1.3 \text{ mol d}^{-1}$ ). During the ice-cover period (28 Nov. 2012–15 Apr. 2013), whole-lake CS increased by 50% from 22 868 mol to 45 951 mol. While during the three-week spring ice-melt period (i.e. 15 Apr.–7 May), 33% of the total whole-lake CO<sub>2</sub> was released, reducing CS to 30 618 mol. This whole-lake CO<sub>2</sub> loss was rapid with  $r$  reaching  $665 \text{ mol d}^{-1}$ . In total, 18 000–23 000 mol of CO<sub>2</sub> was accumulated in the lake during winter of which 15 000 mol was released at ice-melt, and 3000–8000 mol remained in the lake, mainly in the bottom waters (Fig. 4A). Thus, for the sampled period,  $C_{\text{release}}$  was 85%, i.e. 85% of

the total CO<sub>2</sub> accumulated during winter was released at ice-melt.  $C_{\text{release}}$  estimated for the whole ice-cover period equalled 66%.

### CO<sub>2</sub> emission at ice-melt

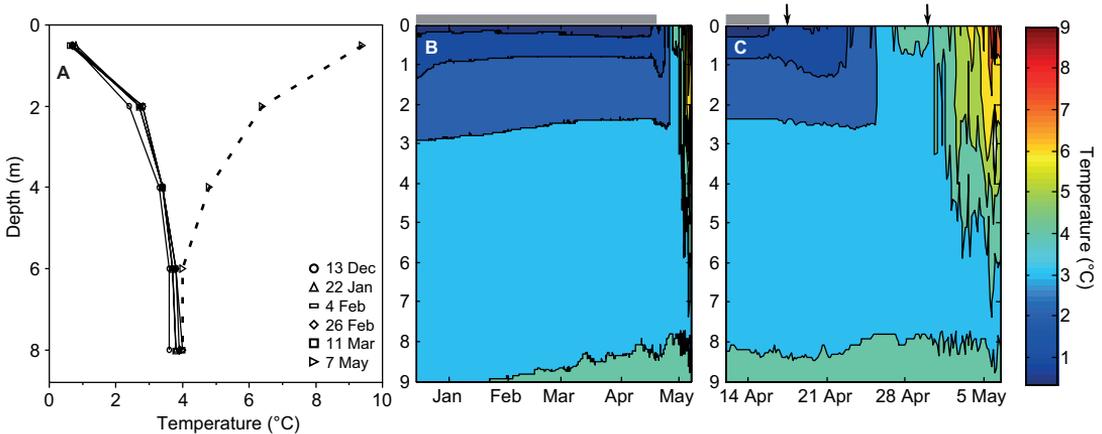
Although the spring emission of CO<sub>2</sub> at ice-melt has the potential to be strong, with a maximum of  $88 \text{ mmol m}^{-2} \text{ d}^{-1}$ , the spring turnover was short and incomplete. During the spring CO<sub>2</sub>-emission period (16 Apr.–4 May), the daily mean  $\pm$  SD  $k_{600}$  was  $2.6 \pm 0.5 \text{ cm h}^{-1}$ , and the daily mean  $\pm$  SD CO<sub>2</sub> concentration  $144 \pm 23 \mu\text{M}$ , which corresponds to a daily mean CO<sub>2</sub> emission of  $38 \pm 11 \text{ mmol m}^{-2} \text{ d}^{-1}$ . During the first peak, accounting for 28%–36% of the total spring CO<sub>2</sub> emissions, the daily mean  $\pm$  SD  $k_{600}$  equalled  $2.7 \pm 0.7 \text{ cm h}^{-1}$ , the daily mean  $\pm$  SD CO<sub>2</sub> concentration  $167 \pm 33 \mu\text{M}$ , and the daily mean  $\pm$  SD CO<sub>2</sub> emission  $44 \pm 16 \text{ mmol m}^{-2} \text{ d}^{-1}$ . During the second peak which accounted for 64%–72% of the total spring CO<sub>2</sub> emissions, the daily mean  $\pm$  SD  $k_{600}$  was  $2.6 \pm 0.4 \text{ cm h}^{-1}$ , the daily mean  $\pm$  SD CO<sub>2</sub> concentration  $136 \pm 11 \mu\text{M}$ , and the daily mean  $\pm$  SD CO<sub>2</sub> emission  $36 \pm 7 \text{ mmol m}^{-2} \text{ d}^{-1}$ .

### Water temperatures below the ice cover

On 13 Dec. (first sampling), the temperature difference between the bottom (8 m) and surface (0.5 m) water layers was greater than 2 °C (Fig. 5A), and this temperature difference remained similar throughout the whole ice-cover season (Fig. 5B). A similar gradient persisting during the entire ice-cover period was observed for oxygen with its content decreasing from the top to bottom waters (data not shown). The temperature difference remained unchanged between the beginning of the ice melt (15 Apr.) and 26 Apr. (Fig. 5C). Thus, water mixing began around 11 days later than the ice-melt.

### Discussion

The surface-water CO<sub>2</sub> concentrations measured continuously at 2 m depth from ice-on to ice-off,



**Fig. 5.** Depth profile of lake-water temperatures measured during (A) field sampling, (B) ice-on to ice-melt period from 22 Jan. to 7 May, 2013, and (C) during spring ice-melt from 13 Apr. to 7 May, 2013. In panel A the dashed line represents field sampling during ice-off. In panels B and C the grey horizontal bars represent ice cover. In panel C the black arrows correspond to CO<sub>2</sub> concentration peaks 3 and 4 in Fig. 2.

showed four distinct phases (Fig. 2). Contradictory to our hypothesis and previous studies (e.g. Huotari *et al.* 2009), continuous CO<sub>2</sub> concentration measurements and whole-lake CO<sub>2</sub> storage estimates below lake ice revealed that CO<sub>2</sub> did not steadily increase throughout the winter (Fig. 2). Rather, CO<sub>2</sub> concentration and whole-lake CO<sub>2</sub> storage increased only in early winter but in late winter the concentrations remained relatively constant after maximum ice thickness had been reached (Table 1 and Fig. 2).

Previous studies in ice-covered lakes found lower concentrations of CO<sub>2</sub> under the ice in late winter, which was attributed to under-ice primary production (Baehr and DeGrandpre 2004, Huotari *et al.* 2009). However, in our lake primary production under ice was highly unlikely, as light intensity was below the detection limits (Fig. 3C) due to thick snow and ice cover (Table 1). Also Sobek *et al.* (2003) found low nutrient concentrations (total phosphorus = 10.8  $\mu\text{g l}^{-1}$ , total nitrogen = 190  $\mu\text{g l}^{-1}$ ) and chlorophyll *a* concentrations being under the detection limit in ice-covered Lake Gaddtjarn.

Since the study lake is small, with a relatively short water residence time (~2 months), and thus substantially affected by the catchment, we suggest that catchment CO<sub>2</sub> inputs (surface and subsurface flow) and biological in-lake CO<sub>2</sub> production are the drivers of surface-water CO<sub>2</sub> accumulation in early winter. Similarly, Karls-

son *et al.* (2013) and Striegl *et al.* (2001) found decomposition of organic matter and CO<sub>2</sub> inputs from the catchment to be important in early winter. Once ice reaches maximum thickness and surrounding soils freeze, water flow from the catchment to the lake is minimized, reducing catchment inputs and mixing of water masses below ice. This is indicated by the stable temperature profile during the entire ice-cover season (Fig. 5B). Dissolved organic matter in waters under ice in late winter has been suggested to have low aromaticity and represent more heavily-degraded material (Mann *et al.* 2012) indicating that substrate availability may be a limiting factor for bacterial respiration in the water column during late winter. This is likely in our lake, since bacterial respiration has been suggested to be limited by temperature and substrate availability (Pomeroy and Wiebe 2001), and surface water temperatures remain constantly low during the ice-cover period (Fig. 5B) while the amount of DOC available to bacterioplankton is decreasing during the ice-cover period (Table 1), and probably also the bioavailability of the remaining DOC is progressively reduced.

Sediments are probably an important source of CO<sub>2</sub> to the water column, as indicated by CO<sub>2</sub> increasing with water depth, and by its accumulation rates in the bottom water being higher than in the surface water (Fig. 4A), which is in line with earlier reports of sediment respiration being

the main source of CO<sub>2</sub> emissions from boreal lakes (Kortelainen *et al.* 2006). The sediments of Lake Gäddejärn are organic-rich and contain ~25% organic carbon (data not shown), and thus represent an environment that is highly enriched in both substrate and nutrients for microbial growth and respiration, leading to substantial CO<sub>2</sub> production. Microbial respiration in sediments is positively and exponentially related to temperature (Gudasz *et al.* 2010, Bergström *et al.* 2010), hence sediment respiration can be expected to be higher in deeper parts of the lake where water temperature is higher (4–5 °C) than in surface water (1–2 °C), contributing to the observed higher CO<sub>2</sub> accumulation rates in the bottom waters in certain periods (Fig. 4A). The decreasing rate of whole-lake CO<sub>2</sub> accumulation (Table 1) may be related to increasing CO<sub>2</sub> concentrations in the bottom water over time (Fig. 4A), since the CO<sub>2</sub> concentration gradient between the sediment and water is reduced when the CO<sub>2</sub> concentration in bottom water increases, thereby reducing the rate of diffusion of CO<sub>2</sub> from the sediment to the bottom water. In other words, increasing bottom-water CO<sub>2</sub> limits further CO<sub>2</sub> diffusion from the sediment. Thus, in this small boreal lake we can divide the ice-cover period into two phases determined by the interplay between biological and physical factors. Similar was proposed by Bertilsson *et al.* (2013).

During late winter, it is likely that localized small-scale physical processes, i.e. water movements, give rise to small-scale oscillations observed in the continuous surface-water CO<sub>2</sub> concentration measurements, rather than biological processes. However, investigation of microbial activity (e.g. respiration rates, isotope analysis) under ice is further needed to confirm this. Nevertheless, physical processes can largely differ among lakes depending on lake morphometry (e.g. Riera *et al.* 1999). In larger and deeper lakes, large-scale physical processes (e.g. internal seiches and deep water turnover) were observed below the ice cover (Baehr and DeGrandpre 2002, and Baehr and DeGrandpre 2004, respectively). However, such processes are less likely to occur in wind-sheltered, small, moderately-shallow lakes such as ours. Hence, differences in physical processes as a result of

differences in lake morphometry might explain why CO<sub>2</sub> accumulation below ice can show very different patterns among lakes.

This is the first study showing that two CO<sub>2</sub> concentration peaks can occur as ice-melt begins, resulting in two potentially distinct events of high CO<sub>2</sub> emission. In contrast, Baehr and DeGrandpre (2004), and Huotari *et al.* (2009) recorded only one CO<sub>2</sub> peak at ice-melt which they attributed to a combination of deep water mixing and net production. However, our continuous CO<sub>2</sub> concentration measurements revealed an unexpected initial peak in surface-water CO<sub>2</sub> on 17 Apr. that was not driven by bottom-water convective turnover, here indicated by temperature differences of more than 2 °C between bottom and surface waters at the time of the first CO<sub>2</sub> concentration peak (Fig. 5C). As ice-melt begins, cold, low-density, lateral catchment inputs of melting snow and stream water (Bengtsson 1996) can increase water column stability and thereby inhibit mixing to deeper layers (Kirillin and Terzhevik 2011). During spring thaw, snow meltwater and stream water have been shown to contain high concentrations of CO<sub>2</sub> (Dinsmore *et al.* 2011, Dinsmore *et al.* 2013, Wallin *et al.* 2013). Thus, we suggest that the first and highest CO<sub>2</sub> concentration peak during ice-melt was a result of small-scale, upper water column mixing of CO<sub>2</sub> transported laterally from the surrounding catchment. CO<sub>2</sub>-rich surface and subsurface inflows and CO<sub>2</sub> mobilized from catchment soils by meltwater enriches littoral zones of a lake with CO<sub>2</sub> and organic matter which is then transported to the central part of the lake. Since this incoming water is cold it will only mix at similar temperature gradients in the upper water column of the lake. During the second CO<sub>2</sub> concentration peak on 30 Apr., however, convective turnover of deep waters becomes important, seen in our data as weakening in thermal stratification beginning on 26 Apr. (Fig. 5C). Thus, in addition to deep-water mixing, our study highlights the importance of lateral CO<sub>2</sub> transport at ice-melt, particularly in small lakes, which have relatively large littoral zones and catchment-to-lake-area ratios, and are the most common lake type worldwide (Downing *et al.* 2006). Studies that investigate lateral CO<sub>2</sub> transport into the lake at ice-melt are valu-

able and these measurements should be included in future studies to estimate their contribution to CO<sub>2</sub> emissions.

During the rapid decline in the CO<sub>2</sub> concentration at ice-off, the maximum CO<sub>2</sub> emission reached 88 mmol m<sup>-2</sup> d<sup>-1</sup>, and the daily mean ± SD CO<sub>2</sub> emission was 38 ± 11 mmol m<sup>-2</sup> d<sup>-1</sup>, which were comparable to the values found for a small boreal lake in Finland after ice breakup (maximum and mean ± SD of 55.6 mmol m<sup>-2</sup> d<sup>-1</sup> and 30.9 ± 16.7 mmol m<sup>-2</sup> d<sup>-1</sup>, respectively; see Huotari *et al.* 2009). Although maximum CO<sub>2</sub> emission rates from our lake can be considered high, spring turnover was incomplete due to rapid warming of surface waters. Thus, as already suggested by Miettinen *et al.* (2015), and indicated by the continuous surface-water CO<sub>2</sub> measurements, high CO<sub>2</sub> emissions at ice-melt during a year with incomplete spring turnover provide some evidence that external sources of CO<sub>2</sub> enter the lake at ice-melt. Further, incomplete turnover resulted in CO<sub>2</sub> remaining in the bottom waters of the lake (Fig. 4A), as not all of the CO<sub>2</sub> accumulated under ice was able to leave the lake at ice out. We estimated that during the ice-cover period (13 Dec. 2012–11 Mar. 2013), 85% of the total CO<sub>2</sub> accumulated below ice in the lake was released at ice-melt. This value was reduced to 66% when the whole ice-cover period (28 Nov. 2012–15 Apr. 2013) was taken into account. Either way, CO<sub>2</sub> remains in the lake and is not released at ice-melt, representing a non-negligible fraction of CO<sub>2</sub> accumulation under ice. These results indicate that the current assumption regarding CO<sub>2</sub> emission estimates that all CO<sub>2</sub> accumulated during the ice-cover period is emitted at ice-melt (e.g. Raymond *et al.* 2013) may not always be true. In our lake, 15%–34% of accumulated CO<sub>2</sub> remained, thus the whole-lake CO<sub>2</sub> storage was 3000–8000 mol higher at ice-off than it was at ice-on. Albeit, the storage of this remaining CO<sub>2</sub> may only be temporary, as CO<sub>2</sub> may be transported downstream or released to the atmosphere during autumn turnover which was shown to be strong (Bellido *et al.* 2009). Alternatively, CO<sub>2</sub> may be internally processed if it is consumed by phytoplankton or undergoes dark carbon fixation (Santoro *et al.* 2013). This result should be interpreted with caution as patterns can differ across lakes and

years. For example, the stability of stratification and the depth of water column mixing at ice-melt have been found to vary between years (Huotari *et al.* 2009, Miettinen *et al.* 2015). Thus, future studies should measure the whole-lake CO<sub>2</sub> storage seasonally over many years to establish long-term patterns.

As compared with the open-water season, identified regulators of winter CO<sub>2</sub> accumulation, biological processes and thermal stratification, are similar. During summer, thermal stratification, and biological processes have been shown to mainly affect CO<sub>2</sub> distribution in the water column of lakes (Weyhenmeyer *et al.* 2012). Our results further suggest that biological processes and thermal stratification affect water-column CO<sub>2</sub> distribution in early and late winter, respectively. Although Schilder *et al.* (2013) found horizontal CO<sub>2</sub> surface water variability during the open-water season, with lower CO<sub>2</sub> concentrations found near-shore than in the middle of the lake, we did not find significant horizontal CO<sub>2</sub> surface water variability under ice (Fig. 4B). In-lake spatial variation during the ice-cover period may be lower than during the open-water season because ice cover creates a cold, dark environment in the lake which reduces variations in physical (e.g. lake mixing) and biological (e.g. metabolism) processes. Also, organic matter degradation in shallow, littoral sediments is greatly reduced at temperatures < 2 °C close to the ice (Gudasz *et al.* 2010). Whereas, during the open-water season, physical and biological processes can greatly vary within the lake (e.g. Hofmann 2013). In addition, we found that the difference in the CO<sub>2</sub> concentrations between the surface and bottom waters increased throughout winter with greatest variability at spring melt when CO<sub>2</sub> was emitted from surface waters. Since horizontal variability was low and vertical variability was large, repeated or continuous measurements at one point but at several depths may be sufficient to calculate whole-lake CO<sub>2</sub> accumulation during the ice-cover period.

In summary, this study showed that (1) CO<sub>2</sub> accumulation is not simply linear under ice, (2) CO<sub>2</sub> was accumulated faster in bottom waters than in surface waters, and (3) at ice-melt, a non-negligible fraction (15%–34%) of CO<sub>2</sub> that

was accumulated under ice was not emitted and remained stored in the bottom waters. These results provide new understanding of lake-water CO<sub>2</sub> distribution patterns under ice and at ice-melt and need to be taken into consideration when estimating annual CO<sub>2</sub> emissions. If up-scaling approaches assume that CO<sub>2</sub> accumulates linearly under ice and that all CO<sub>2</sub> accumulated during the ice-cover period leaves the lake at ice-melt, present estimates may overestimate CO<sub>2</sub> emissions from small, ice-covered lakes. Likewise, neglecting CO<sub>2</sub> at ice-melt will result in an underestimation of CO<sub>2</sub> emissions from small ice-covered lakes. Comparative studies are further needed to advance our understanding of difference in CO<sub>2</sub> accumulation patterns across lake type and region. How much changes in the duration of the ice-cover period in a warmer climate will affect the balance between winter CO<sub>2</sub> accumulation and spring CO<sub>2</sub> outburst remains to be studied.

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## References

- Aufdenkampe A.K., Mayorga E., Raymond P.A., Melack J.M., Doney S.C., Alin S.R., Aalto R.E. & Yoo K. 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment* 9: 53–60.
- Baehr M.M. & DeGrandpre M.D. 2002. Under-ice CO<sub>2</sub> and O<sub>2</sub> variability in a freshwater lake. *Biogeochemistry* 61: 95–113.
- Baehr M.M. & DeGrandpre M.D. 2004. In situ pCO<sub>2</sub> and O<sub>2</sub> measurements in a lake during turnover and stratification: observations and modeling. *Limnology and Oceanography* 49: 330–340.
- Battin T.J., Luyssaert S., Kaplan L.A., Aufdenkampe A.K., Richter A. & Tranvik L.J. 2009. The boundless carbon cycle. *Nature Geoscience* 2: 598–600.
- Bellido J.L., Tulonen T., Kankaala P. & Ojala A. 2009. CO<sub>2</sub> and CH<sub>4</sub> fluxes during spring and autumn mixing periods in a boreal lake (Pääjärvi, southern Finland). *Journal of Geophysical Research-Biogeosciences* 114: G04007, doi: 04010.101029/02009JG000923.
- Belzile C., Vincent W.F., Gibson J.A.E. & Hove P.V. 2001. Bio-optical characteristics of the snow, ice, and water column of a perennially ice-covered lake in the High Arctic. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 2405–2418.
- Bengtsson L. 1996. Mixing in ice-covered lakes. *Hydrobiologia* 322: 91–97.
- Bergström I., Kortelainen P., Sarvala J. & Salonen K. 2010. Effect of temperature and sediment properties on benthic CO<sub>2</sub> production in an oligotrophic boreal lake. *Freshwater Biology* 55: 1747–1757.
- Bertilsson S., Burgin A., Carey C.C., Fey S.B., Grossart H.P., Grubisic L.M., Jones I.D., Kirillin G., Lennon J.T., Shade A. & Smyth R.L. 2013. The under-ice microbiome of seasonally frozen lakes. *Limnology and Oceanography* 58: 1998–2012.
- Butman D. & Raymond P.A. 2011. Significant efflux of carbon dioxide from streams and rivers in the United States. *Nature Geoscience* 4: 839–842.
- Cole J.J. & Caraco N.F. 1998. Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of SF<sub>6</sub>. *Limnology and Oceanography* 43: 647–656.
- Cole J.J., Caraco N.F., Kling G.W. & Kratz T.K. 1994. Carbon dioxide supersaturation in the surface waters of lakes. *Science* 265: 1568–1570.
- Cole J.J., Prairie Y.T., Caraco N.F., McDowell W.H., Tranvik L.J., Striegl R.G., Duarte C.M., Kortelainen P., Downing J.A., Middelburg J.J. & Melack J. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10: 172–185.
- Demarty M., Bastien J. & Tremblay A. 2011. Annual follow-up of gross diffusive carbon dioxide and methane emissions from a boreal reservoir and two nearby lakes in Québec, Canada. *Biogeosciences* 8: 41–53.
- Dinsmore K.J., Billett M.F., Dyson K.E., Harvey F., Thomson A.M., Piirainen S. & Kortelainen P. 2011. Stream water hydrochemistry as an indicator of carbon flow paths in Finnish peatland catchments during a spring snowmelt event. *Science of the Total Environment* 409: 4858–4867.
- Dinsmore K.J., Wallin M.B., Johnson M.S., Billett M.F., Bishop K., Pumpanen J. & Ojala A. 2013. Contrasting CO<sub>2</sub> concentration discharge dynamics in headwater streams: A multi-catchment comparison. *Journal of Geophysical Research, Biogeosciences* 118: 445–461.
- Downing J.A., Prairie Y.T., Cole J.J., Duarte C.M., Tranvik L.J., Striegl R.G., McDowell W.H., Kortelainen P., Caraco N.F., Melack J.M. & Middelburg J.J. 2006. The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography* 51: 2388–2397.
- Gudasz C., Bastviken D., Steger K., Premke K., Sobek S. & Tranvik L.J. 2010. Temperature-controlled organic carbon mineralization in lake sediments. *Nature* 466:

- 478–481.
- Gunn J. & Keller W. 1985. Effects of ice and snow cover on the chemistry of nearshore lake water during spring melt. *Annals of Glaciology* 7: 208–212.
- Hofmann H. 2013. Spatiotemporal distribution patterns of dissolved methane in lakes: how accurate are the current estimations of the diffusive flux path? *Geophysical Research Letters* 40: 2779–2784.
- Huotari J., Ojala A., Peltomaa E., Pumpanen J., Hari P. & Vesala T. 2009. Temporal variations in surface water CO<sub>2</sub> concentration in a boreal humic lake based on high-frequency measurements. *Boreal Environment Research* 14: 48–60.
- Jähne B., Heinz G. & Dietrich W. 1987. Measurements of the diffusion coefficients of sparingly soluble gases in water. *Journal of Geophysical Research* 92: 10767–10776.
- Johnson M.S., Billett M.F., Dinsmore K.J., Wallin M., Dyson K.E. & Jassal R.S. 2010. Direct and continuous measurement of dissolved carbon dioxide in freshwater aquatic systems—method and applications. *Ecohydrology* 3: 68–78.
- Karlsson J., Ask J. & Jansson M. 2008. Winter respiration of allochthonous and autochthonous organic carbon in a subarctic clear-water lake. *Limnology and Oceanography* 53: 948–954.
- Karlsson J., Giesler R., Persson J. & Lundin E. 2013. High emission of carbon dioxide and methane during ice thaw in high latitude lakes. *Geophysical Research Letters* 40: 1123–1127.
- Kirillin G. & Terzhevik A. 2011. Thermal instability in freshwater lakes under ice: Effect of salt gradients or solar radiation? *Cold Regions Science and Technology* 65: 184–190.
- Kokic J., Wallin M., Chmiel H.E., Denfeld B.A. & Sobek S. 2015. Carbon dioxide evasion from headwater systems strongly contributes to the total export of carbon from a small boreal lake catchment. *Journal of Geophysical Research, Biogeosciences* 120: 13–28.
- Kortelainen P., Rantakari M., Huttunen J.T., Mattsson T., Alm J., Juutinen S., Larmola T., Silvola J. & Martikainen P.J. 2006. Sediment respiration and lake trophic state are important predictors of large CO<sub>2</sub> evasion from small boreal lakes. *Global Change Biology* 12: 1554–1567.
- Krenz J. 2013. *Measuring CO<sub>2</sub> emissions from a small boreal lake and its connecting streams using automatic floating chambers*. Swedish University of Agriculture Sciences, Uppsala.
- Mann P.J., Davydova A., Zimov N., Spencer R.G.M., Davydov S., Bulygina E., Zimov S. & Holmes R.M. 2012. Controls on the composition and lability of dissolved organic matter in Siberia's Kolyma River basin. *Journal of Geophysical Research* 117: G01028, doi:10.1029/2011JG001798.
- Michmerhuizen C.M., Striegl R.G. & McDonald M.E. 1996. Potential methane emission from north-temperate lakes following ice melt. *Limnology and Oceanography* 41: 985–991.
- Miettinen H., Pumpanen J., Heiskanen J.J., Aaltonen H., Mammarella I., Ojala A., Levula J. & Rantakari M. 2015. Towards a more comprehensive understanding of lacustrine greenhouse gas dynamics — two-year measurements of concentrations and fluxes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O in a typical boreal lake surrounded by managed forests. *Boreal Environment Research* 20: 75–89.
- Pomeroy L.R. & Wiebe W.J. 2001. Temperature and substrates as interactive limiting factors for marine heterotrophic bacteria. *Aquatic Microbial Ecology* 23: 187–204.
- Raymond P.A., Hartmann J., Lauerwald R., Sobek S., McDonald C., Hoover M., Butman D., Striegl R., Mayorga E., Humborg C., Kortelainen P., Durr H., Meybeck M., Ciais P. & Guth P. 2013. Global carbon dioxide emissions from inland waters. *Nature* 503: 355–359.
- Riera J.L., Schindler J.E. & Kratz T.K. 1999. Seasonal dynamics of carbon dioxide and methane in two clear-water lakes and two bog lakes in northern Wisconsin, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 56: 265–274.
- Rouse W.R., Oswald C.J., Binyamin J., Spence C.R., Schertzer W.M., Blanken P.D., Bussières N. & Duguay C.R. 2005. The role of northern lakes in a regional energy balance. *Journal of Hydrometeorology* 6: 291–305.
- Santoro A.L., Bastviken D., Gudasz C., Tranvik L. & Enrich-Prast A. 2013. Dark carbon fixation: an important process in lake sediments. *PLoS ONE* 8: e65813, doi:10.1371/journal.pone.0065813.
- Schilder J., Bastviken D., van Hardenbroek M., Kankaala P., Rinta P., Stotter T. & Heiri O. 2013. Spatial heterogeneity and lake morphology affect diffusive greenhouse gas emission estimates of lakes. *Geophysical Research Letters* 40: 5752–5756.
- Sellers P., Hesslein R.H. & Kelly C.A. 1995. Continuous measurement of CO<sub>2</sub> for estimation of air–water fluxes in lakes: An in situ technique *Limnology and Oceanography* 40: 575–581.
- Sobek S., Algesten G., Bergstrom A.K., Jansson M. & Tranvik L.J. 2003. The catchment and climate regulation of pCO<sub>2</sub> in boreal lakes. *Global Change Biology* 9: 630–641.
- Striegl R.G. & Michmerhuizen C.M. 1998. Hydrologic influence on methane and carbon dioxide dynamics at two north-central minnesota lakes. *Limnology and Oceanography* 43: 1519–1529.
- Striegl R.G., Kortelainen P., Chanton J.P., Wickland K.P., Bugna G.C. & Rantakari M. 2001. Carbon dioxide partial pressure and <sup>13</sup>C content of north temperate and boreal lakes at spring ice melt. *Limnology and Oceanography* 46: 941–945.
- Tranvik L.J., Downing J.A., Cotner J.B., Loiselle S.A., Striegl R.G., Ballatore T.J., Dillon P., Finlay K., Fortino K., Knoll L.B., Kortelainen P.L., Kutser T., Larsen S., Laurion I., Leech D.M., McCallister S.L., McKnight D.M., Melack J.M., Overholt E., Porter J.A., Prairie Y., Renwick W.H., Roland F., Sherman B.S., Schindler D.W., Sobek S., Tremblay A., Vanni M.J., Verschoor A.M., von Wachenfeldt E. & Weyhenmeyer G.A. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography* 54: 2298–2314.
- Wallin M.B., Grabs T., Buffam I., Laudon H., Agren A., Oquist M.G. & Bishop K. 2013. Evasion of CO<sub>2</sub> from streams — the dominant component of the carbon export

- through the aquatic conduit in a boreal landscape. *Global Change Biology* 19: 785–797.
- Weiss R.F. 1974. Carbon dioxide in water and seawater: the solubility of a non-ideal gas. *Marine Chemistry* 2: 203–215.
- Weyhenmeyer G.A., Kortelainen P., Sobek S., Müller R. & Rantakari M. 2012. Carbon dioxide in boreal surface waters: a comparison of lakes and streams. *Ecosystems* 15: 1295–1307.
- Weyhenmeyer G.A., Livingstone D.M., Meili M., Jensen O., Benson B. & Magnuson J.J. 2011. Large geographical differences in the sensitivity of ice-covered lakes and rivers in the northern hemisphere to temperature changes. *Global Change Biology* 17: 268–275.