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LETTER

Ice-melt period dominates annual carbon dioxide evasion from clear-water Arctic lakes

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Scientific Significance Statement

Arctic lakes are thought to release a significant amount of carbon dioxide (CO_2) into the atmosphere. However, current estimates are uncertain because most studies occur during the summer months, and the CO_2 that accumulates in winter and largely evades to the atmosphere within a few days when ice melts in spring is rarely quantified. In a study of 14 Arctic lakes, we show that the ice-melt period dominates (mean 80%) annual CO_2 evasion. Comparisons with previous studies reveal that ice-melt CO_2 evasion is particularly important in clear-water organic carbon-poor lakes, which are abundant in the Arctic, and decreases toward more colored organic carbon-rich lakes. The results stress that overlooking the high share of CO_2 evasion at ice-melt likely underestimates CO_2 release to the atmosphere from Arctic lakes.

Abstract

Current estimates of carbon dioxide (CO_2) evasion from Arctic lakes are highly uncertain because few studies integrate seasonal variability, specifically evasion during spring ice-melt. We quantified annual CO_2 evasion for 14 clear-water Arctic lakes in Northern Sweden through mass balance (ice-melt period) and high-frequency loggers (open-water period). On average, 80% (SD: $\pm$ 18) of annual CO_2 evasion occurred within 10 d following ice-melt. The contribution of the ice-melt period to annual CO_2 evasion was high compared to earlier studies of Arctic lakes (47% $\pm$ 32%). Across all lakes, the proportion of ice-melt : annual CO_2 evasion was negatively related to the dissolved organic carbon concentration and positively related to the mean depth of the lakes. The results emphasize the need for measurements of CO_2 exchange at ice-melt to accurately quantify CO_2 evasion from Arctic lakes.

Lakes emit significant amounts of greenhouse gases into the atmosphere (Raymond et al. 2013). The gas evasion is dominated by carbon dioxide (CO_2) and driven by the input of inorganic and organic carbon (C) from land (Tranvik et al. 2009). High-latitude lakes are abundant (Verpoorter et al. 2014), generally small (Muster et al. 2019), and with

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Additional Supporting Information may be found in the online version of this article.

close hydrological connectivity to terrestrial ecosystems, facilitating the input and evasion of land-derived C forms in these lakes (Vachon et al. 2017). The pronounced warming at high latitudes is expected to affect terrestrial C cycling and lateral C export, but also the mineralization and evasion of this C in lakes (Williamson et al. 2008). It is, therefore, important to quantify and understand lake C evasion to accurately assess the contemporary and future Arctic C cycle.

Many lakes show strong temporal variability in atmospheric CO_2 exchange. For northern lakes, especially with long winter and ice-covered periods, CO_2 accumulates under ice and is largely released during a short period following ice-melt in spring (Striegl and Michmerhuizen 1998; Karlsson et al. 2013). The CO_2 accumulation during winter and subsequent evasion at ice-melt generally increases with lake mean depth (Karlsson et al. 2013; Ducharme-Riel et al. 2015). A synthesis of data reported that ice-melt CO_2 evasion constituted, on average, 17% of annual evasion in northern lakes, with especially high values in the Arctic (34%) compared to boreal (16%) and temperate (22%) lakes (Denfeld et al. 2018). However, this synthesis only included 18 Arctic lakes, and recent studies in clear-water Arctic lakes with low content of dissolved organic C (DOC) reported higher values (58% $\pm$ 32% in 14 Swedish lakes, Verheijen et al. 2022; 51% and 71% in 2 Canadian lakes, Preskienis et al. 2021). The importance of ice-melt evasion could thus be undervalued given the abundance of low DOC lakes (median DOC < 5 mg L^{-1}) in the Arctic compared to other biomes (Sobek et al. 2007), calling for specific investigation of the importance of ice-melt evasion in these types of systems. However, most assessments of CO_2 evasion from lakes, including in the Arctic, neglect seasonal variability in CO_2 fluxes, focusing instead on a limited number of sampling occasions during the summer (Klaus et al. 2019). This implies that current assessments of lake CO_2 evasion are likely underestimates, especially in clear-water Arctic lakes.

The aim of this study was to investigate the ice-melt contribution to annual CO_2 evasion from Arctic clear-water, low DOC lakes. We quantified the annual CO_2 exchange for 14 clear-water lakes in northern Sweden based on dissolved inorganic C (DIC) mass balance during the ice-melt period and high-frequency logging during the open-water period and compared the results to published data to explore general patterns in ice-melt CO_2 evasion across Arctic lakes.

Methods

Study lakes

The 14 lakes are about 250 km north of the Arctic Circle in northern Sweden and range from 1.6 to 11.4 ha in surface area, 2.3 to 20.5 m in maximum depth (Table 1), and are ice-covered for > 50% of the year (SMHI 2006). The dominant land cover in the lake catchments is forests dominated by birch trees (*Betula* spp.) and Arctic heath (*Vaccinium* spp., *Empetrum* spp.), along with intermittent areas of bare rock (Supporting Information Table S1). Mean annual precipitation during 1960–1990 varied between 500 and 900 mm in the region, with > 45% as snow (https://www.smhi.se/).

Sampling

Sampling was conducted at the deepest point of each lake between June and October 2018 (open water), and in late March to early April (on safe ice before ice-melt) and in June 2019 (within 10 d after ice-melt). We collected water chemistry samples and measured physicochemical parameters in each season and deployed loggers for continuous data collection during the open-water period (detailed below). Depth profiles of temperature were measured every 0.5 m (0–4 m) or 1 m (4–10 m) using an optical sensor (ProDO; YSI). Photosynthetically active radiation (PAR) was measured every 0.5 m between 0 and 3 m using a LI-193 Spherical Quantum Sensor (LI-COR Environmental). The vertical light attenuation coefficient (K_d) of the 0–3 m water column was calculated as the slope between the natural logarithm of PAR against depth. We collected (Ruttner sampler, HannaNorden AB) water from 1 m beneath the lake surface or (in winter) beneath the bottom of the ice (representing epilimnion) and 1 m above the lake bottom (representing hypolimnion). For DIC, we injected 4 mL into airtight 20 mL borosilicate glass vials, pre-flushed with N_2 and containing 100 μL 1.2 mol L^{-1} HCl. Epilimnion and hypolimnion samples were pooled and subsampled for analysis of DOC (0.45 μm filtered, acidified), absorbance at 440 nm (a_{440}, 0.45 μm filtered), and total nitrogen (TN) and phosphorus (TP) at the Biogeochemical Analytical Facility at Umeå University following Verheijen et al. (2022).

Continuous data collection

As soon as possible after the ice breakup in 2018, a cup anemometer (S-WSA-M003, ONSET Corporation) was deployed 2 m above the ground < 15 m from the shoreline of each lake. The CO_2 concentration of the surface water at the deepest point of each lake was recorded hourly during the open-water season of 2018 using a floating chamber ($8 \times 8 \times 11$ cm^3) equipped with a CO_2-logger (K33 ELG; Senseair AB). The floating chamber was equipped with an internal drying chamber to prevent water from reaching the CO_2 sensor. Each hour, 150 cm^3 of headspace was pumped from the chamber over a period of 30 s through a silica-filled drying chamber before reaching the CO_2 sensor and then looped back into the chamber. For further details of the chamber design, *see* Verheijen et al. (2022). Surface water temperature was measured every 5 min by a logger (Hobo TidbiT v2; ONSET Corporation) deployed next to the chamber. Continuous data collection of CO_2 was also carried out in 2019 for 11 of the lakes, but these data are only used for the discussion of the timing of DIC sampling after the ice-off in 2019.

Table 1. Physical and chemical characteristics and CO_2 evasion of the 14 study lakes.

Lake	Mean depth (m)	DOC (mg L^{-1})	K_d (m^{-1})	a_{440} (m^{-1})	Ice-melt evasion (g C m^{-2} yr^{-1})	Annual evasion (g C m^{-2} yr^{-1})
BD01	2.9	1.3	0.4	0.1	18.4	18.0
BD02	7.2	1.1	0.5	0.2	9.0	9.7
BD03	2.0	1.7	0.5	0.3	5.5	7.0
BD04	2.3	2.8	0.7	0.6	5.9	9.0
BD05	6.6	1.5	0.4	0.3	19.8	22.7
BD06	2.8	2.0	0.5	0.3	8.8	10.2
BD07	6.5	2.6	0.8	0.6	20.9	22.8
BD08	0.8	5.8	1.1	1.2	10.2	12.0
BD09	1.2	4.9	1.2	1.1	3.7	7.3
BD10	2.2	3.7	0.8	0.8	6.7	5.8
BD11	3.3	4.9	1.0	1.2	13.0	18.1
BD12	1.4	5.3	1.0	1.1	2.7	5.3
BD13	2.6	5.2	1.0	1.3	6.7	12.2
BD14	5.5	1.8	0.5	0.1	29.9	23.3

Lakes that were headwater lakes (i.e., had no lakes upstream) are marked in bold.
DOC, dissolved organic carbon; K_d, vertical light attenuation coefficient; a_{440}, absorbance at 440 nm.

Calculation of CO_2 fluxes

The methods for data handling and calculation of CO_2 fluxes are described in Supporting Information Text S2 and Verheijen et al. (2022). Briefly, CO_2 fluxes between the lake and atmosphere during the open-water season of 2018 (excluding the short ice-melt period) were estimated using Fick's first law of diffusion coupled with a wind-based model to determine piston velocity, *k* (Cole and Caraco 1998; Wanninkhof 2014). The total open-water CO_2 flux was calculated as the sum of all measured open-water CO_2 fluxes (excluding the days before the first DIC sampling following ice-melt). The CO_2 evasion at ice-melt 2019 was estimated as the difference between DIC inventory before and after ice-melt. We depth-integrated epi- and hypolimnion DIC concentrations over the respective volume of each layer to calculate DIC inventories. Epi- and hypolimnion volumes were determined using the function *thermo.depth* within the R package 'Rlakeanalyzer' (Read et al. 2011). We compared the results of density thresholds of 0.01–0.1 kg m^{-3} m^{-1}, yielding no differences in thermocline depths. Ice duration was inferred from satellite images (Supporting Information Text S1).

Statistics

We analyzed our data using R v 3.6.1 (R Core Development Team 2020). The data are archived on Zenodo (Karlsson et al. 2023). We tested for relationships between CO_2 evasion at ice-melt and in the open-water period, the proportion of annual CO_2 evaded during ice-melt, and their potential drivers using generalized least-squares linear regression analysis by means of the "gls" function in R. As family objects we used "Gaussian" with the "identity" link function for continuous variables and "binomial" with the "logit" link function for proportional variables. We $\log_{10}$ transformed data to conform with model assumptions, if necessary. We compared the proportion of annual flux evaded during ice-melt in relation to DOC concentration and mean depth in our study with previously published results from Arctic lakes. We compared the fits of single-variable models (DOC and mean depth) and of the model with both variables included (using the likelihood ratio test for nested models by means of the "lmtest" package in R). Two lakes were included in multiple studies, and in the statistical analyses, we included the data with the highest temporal resolution. We carried out the comparison with and without non-headwater lakes. The rationale is that the CO_2 evasion from non-headwater lakes is not only dependent on their intrinsic properties but also on the C cycling in, and export from, upstream lakes.

Results

The lakes generally had clear water (Table 1, average $K_d = 0.8$ m^{-1}, $a_{440} = 0.7$ m^{-1}), with low concentrations of DOC (Table 1, average 3.2 mg L^{-1}) and nutrients (TN = 140 μg L^{-1}, TP = 1 μg L^{-1}; Supporting Information Table S1). The lakes of this study are representative in terms of mean depth (Table 2; globally: 99% < 10.4 m; Cael et al. 2017), surface area (Arctic: 53% within 0.01–0.1 km^2; Paltan et al. 2015), and DOC (Arctic: 72% < 7.4 mg L^{-1}; Klaus et al. 2021). A strong relationship between DOC and K_d ($R^2 = 0.93$, $p < 0.01$) suggests that water clarity and DOC content are predominantly controlled by variation in terrestrial colored DOC input, in line with previous findings showing a terrestrially dominated stable C isotopic

Table 2. Mean ice-melt CO_2 evasion and its contribution (%) to annual CO_2 evasion, in this and previous studies of Arctic headwater lakes (values for all lakes, including both headwater and non-headwaters lakes, are given in parenthesis).

		Ice-melt CO_2 evasion				
Study	***n***	**g C m^{-2} yr^{-1}**	**% of annual**	**DOC (mg L^{-1})**	**Mean depth (m)**	**Lake area (km^2)**
This study	11 (14)	10.9 (11.5)	80 (79)	3.3 (3.2)	3.1 (3.4)	0.06 (0.06)
Karlsson et al. (2010)	1	8.1	28	7.2	2.0	0.02
Karlsson et al. (2013)	6 (12)	2.7 (4.1)	20 (43)	8.8 (9.1)	1.3 (1.4)	0.05 (0.05)
Jansen et al. (2019)	2 (3)	19 (28.5)	23 (21)	7.8 (7.8)	1.4 (1.5)	0.10 (0.07)
Preskienis et al. (2021)	2	40.1	61	4.4	2.5	0.07
Verheijen et al. (2022)	11 (14)	4.8 (5.9)	54 (57)	4.8 (5.0)	3.5 (3.4)	0.07 (0.07)
Total	33 (46)					
Average		9.6 (10.1)	55 (58)	5.2 (5.7)	2.7 (2.7)	0.06 (0.06)

n Refers to the number of individual lakes sampled in each study. Jansen et al. (2019) do not include DOC, and for these lakes, we include the DOC data from Karlsson et al. (2013).

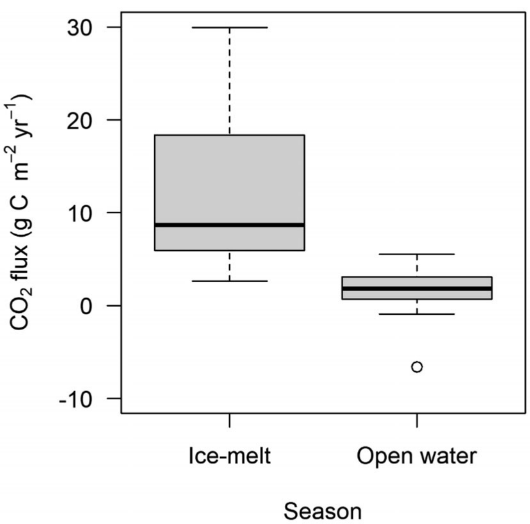

Fig. 1. The total CO_2 flux during ice-melt and open-water season. Positive values indicate flux from the lake to the atmosphere, and negative values indicate the reverse flux. The boxes indicate the upper and lower quartile, the horizontal line the median, the whiskers illustrate 1.5 times the interquartile range, and circles are outliers beyond the whiskers.

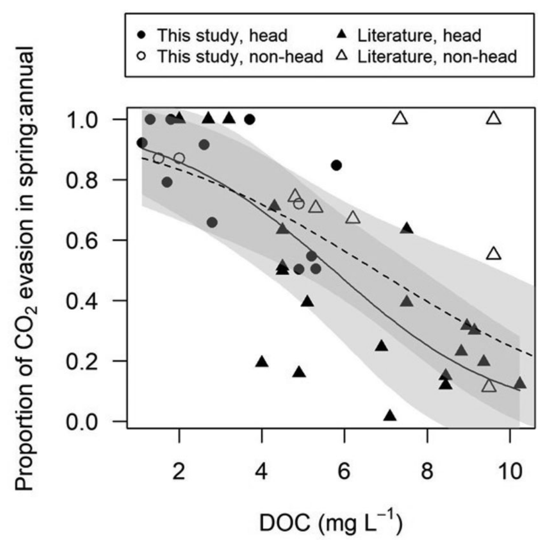

Fig. 2. The contribution of ice-melt period to the annual CO_2 evasion in Arctic lakes plotted against DOC concentration. Sources of published data are given in Table 2. The solid (headwater lakes) and hatched (all lakes) lines and shading represent the mean and 95% confidence interval of generalized linear model predictions.

composition of DOC and low phytoplankton biomass in lakes in the region (Karlsson et al. 2003).

Lake CO_2 evasion was relatively high during ice-melt and relatively low (or in three cases negative) during the rest of the open-water season period (Fig. 1; Table 1). The average CO_2 evasion was 11.5 ± 7.9 g C m^{-2} yr^{-1} at ice-melt and 1.6 ± 3 g C m^{-2} yr^{-1} over the open-water period. Although some lakes were net CO_2 sinks during the open-water period, all were net sources of CO_2 to the atmosphere on an annual scale. The CO_2 evasion during ice-melt was positively related to $\log_{10}$(mean depth) (generalized least-squares linear regression, $R^2 = 0.430$, $p = 0.0151$) but not related to DOC ($R^2 = 0.224$, $p = 0.093$). In partial contrast, the CO_2 flux during the open-water season was not related to mean depth ($R^2 = 0.08$, $p = 0.34$) or to DOC ($R^2 = 0.25$, $p = 0.068$).

The ice-melt evasion was comparable to previous studies of Arctic lakes, yet the degree to which it contributed to the annual CO_2 evasion was higher than previously reported ($80\% \pm 18\%$ vs. $47\% \pm 32\%$, Table 2). The proportion of annual CO_2 evaded during ice-melt for all lakes was negatively related to DOC ($R^2 = 0.42$, $p = 0.011$, Fig. 2) and positively related to $\log_{10}$(mean depth) ($R^2 = 0.29$, $p = 0.029$). The relationships were stronger when excluding lakes with upstream lakes and only including headwater lakes (DOC: $R^2 = 0.63$, $p = 0.009$; $\log_{10}$(mean depth): $R^2 = 0.37$, $p = 0.038$).

Comparing the fits of single and dual variable models yields no improvement in adding mean depth to the DOC model (likelihood ratio test, $\chi^2 = 0.45$, $p = 0.50$), but a significant improvement of adding DOC to the mean depth model ($\chi^2 = 10.2$, $p = 0.0014$). This suggests that DOC is the superior explanatory variable. Given that the lakes experience similar climatic conditions, it is unlikely that variation in ice-cover duration (Supporting Information Text S1) has any major impact on the results.

Discussion

There were pronounced seasonal patterns in atmospheric CO_2 exchange for most of the lakes, with particularly high CO_2 evasion during ice-melt in spring and relatively low and stable CO_2 fluxes during the rest of the open-water season (Fig. 1; Supporting Information Fig. S1). We did not observe any marked peaks in CO_2 evasion in autumn. Such peaks can be especially pronounced in lakes at lower latitudes as CO_2 accumulated in the hypolimnion during the summer is released by water column mixing during the autumn (Klaus et al. 2019). The lack of autumn peaks in our data likely reflects the relatively short period with stable thermal stratification and low net CO_2 production rates in the study lakes (Klaus et al. 2021; Klaus et al. 2022). The short episodic CO_2 evasion during ice-melt represented, on average, 80% of the annual evasion from these lakes. As three of the lakes were net CO_2 sinks during the open-water season (Table 1), neglecting the ice-melt evasion would erroneously classify them as CO_2 sinks.

The mass balance of DIC or CO_2 is commonly used for estimating ice-melt CO_2 evasion, yet it includes uncertainties. The DIC under ice was taken between late March and early April, as melting conditions later in the season caused difficulties in reaching the lakes and carrying out the sampling in a safe manner. This may have led to errors in calculated CO_2 evasion at ice-melt due to processes such as organic C mineralization and methane oxidation (resulting in underestimation) or photosynthetic CO_2 uptake (resulting in overestimation) under ice following sampling. Groundwater input may also cause errors depending on its magnitude and CO_2 content relative to lake volume and CO_2 content. We lack data to evaluate the net effect of these processes, which can be assumed to vary across lakes. Furthermore, the DIC after ice-melt was for most lakes taken within 10 d after the lakes became ice-free, assuming the entire column was equilibrated with the atmosphere. This is supported by pCO_2 having decreased by the time DIC was sampled (Supporting Information Fig. S2) and by calculated theoretical water column equilibration times (Z_{mean}/k) of on average 5.6 ± 3.9 d using the most conservative k model (Cole and Caraco 1998). Although this theoretical assessment contains uncertainties, it suggests that sampling within 10 d after ice-melt represents a compromise between maximizing the time to capture ice-melt evasion and minimizing the time to avoid potential effects of other processes on the DIC mass balance. Still, part of the stored CO_2 under the ice is likely exported downstream rather than emitted following ice-melt. The uncertainties emphasize the need to assess the validity of the mass balance method, as well as to develop methods for direct measurements, for quantification of CO_2 evasion from Arctic lakes during ice-melt (Denfeld et al. 2018).

Since we do not have data on the potential CO_2 sources and sinks on an annual scale, we can only speculate on the drivers of the patterns in CO_2 exchange across lakes. The generally low DOC concentration implies relatively low net CO_2 production in the lakes (Ask et al. 2012). Comparison with published data on net ecosystem production from the study lakes (Klaus et al. 2022) shows that internal CO_2 production during the open-water season is not sufficient to support annual CO_2 evasion (average 34% of CO_2 evasion) except for in two lakes. Although net ecosystem production during winter is unknown, it is reasonable to assume that external CO_2 input is an important contributor to CO_2 evasion from these relatively low DOC lakes. Regional stream studies generally show high stream water concentrations of DIC and CO_2 in winter and low concentrations in summer, while DOC exhibits the opposite pattern (Karlsson et al. 2013; Giesler et al. 2014). This suggests contrasting seasonal patterns in inorganic vs. organic C export from soils to lakes, which, in turn, could facilitate relatively high ice-melt : annual CO_2 evasion ratios from lakes.

It is also possible that primary production in the open-water season can play a role in the seasonal CO_2 exchange dynamics. While these lakes are nutrient-poor, favorable light conditions can maintain high growth rates by benthic algae that have access to nutrients in sediments (Hansson 1992; Vadeboncoeur et al. 2003). Published values of summer gross primary production (Klaus et al. 2022) in the lakes are similar to the CO_2 evasion at ice-melt presented in this paper. Although the generated autochthonous organic C is to some degree mineralized in the open-water season and stored in sediments, previous studies of high-latitude lakes show that autochthonous organic C generated in summer can be at least partly mineralized and contribute to the CO_2 accumulation in winter (Karlsson et al. 2008; Bogard et al. 2019).

Taken together, we hypothesize that in clear-water Arctic lakes, the importance of external CO_2 supply over internal mineralization of terrestrial organic C, and production and recycling of autochthonous organic C, both favor a high proportion of ice-melt period to annual CO_2 evasion. In lakes with higher DOC content, the internal mineralization of terrestrial organic C could play a larger overall role in CO_2 evasion, and this likely takes place predominately during the warmer open-water season with elevated DOC input, resulting in lower ice-melt : annual CO_2 evasion ratios. Furthermore, the CO_2 evasion at ice-melt was positively correlated to lake depth, in agreement with previous studies (Karlsson et al. 2013; Ducharme-Riel et al. 2015). Although the model did not find a strong relationship between depth and the seasonal CO_2 dynamics in these lakes, depth likely contributed to the observed patterns with higher ice-melt : annual CO_2 evasion ratios in deep vs. shallow systems. Studies of the sources and control of CO_2 exchange in various lakes over the years are needed to improve our understanding of C cycling in Arctic lakes.

Based on the results, we suggest that CO_2 evasion during ice-melt is of particular importance for annual evasion in small clear-water Arctic lakes. As the study lakes were representative in size, depth, and DOC, the results should be applicable to a broad range of lakes in the Arctic and call for reassessment of CO_2 evasion from Arctic lakes. Yet, although the inverse relationship with DOC suggests underestimation of current CO_2 flux data based on open-water measurements in the abundant clear-water lakes, this effect is likely partly counteracted due to lakes with low DOC often having lower overall CO_2 evasion compared to lakes with high DOC (Raymond et al. 2013; Lundin et al. 2015). Irrespective, as the majority of global lakes are located at high latitudes and have a long ice-covered period (Denfeld et al. 2018), accounting for the high episodic CO_2 evasion is essential for global estimates of lake CO_2 evasion.

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