Review Paper

Methane emissions from northern lakes under climate change: a review

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Abstract
Northern lakes are important sources of CH_4 in the atmosphere under the background of permafrost thaw and winter warming. We synthesize studies on thermokarst lakes, including various carbon sources for CH_4 emission and the influence of thermokarst drainage on carbon emission, to show the evasion potential of ancient carbon that stored in the permafrost and CH_4 emission dynamics along with thermokarst lake evolution. Besides, we discuss the lake CH_4 dynamics in seasonally ice-covered lakes, especially for under-ice CH_4 accumulation and emission during spring ice melt and the possible influential factors for CH_4 emission in ice-melt period. We summarize the latest findings and point out that further research should be conducted to investigate the possibility of abundant ancient carbon emission from thermokarst lakes under climate warming and quantify the contribution of ice-melt CH_4 emission from northern lakes on a large scale.

Keywords CH_4 emission · Northern lakes · Permafrost thaw · Ice coverage · Climate change

1 Introduction

Atmospheric CH_4 is the second major greenhouse gas, with 32 times higher global-warming potential than CO_2 for a 100-year time horizon, and contributes to about 23% to the additional radiative forcing accumulated in the lower atmosphere since 1750 [25]. Over the past two decades, surface freshwaters including lakes, reservoirs, and rivers have been recognized as important global CH_4 sources [4, 70], whereas the contribution of northern lakes is neglected and overshadowed by wetland emission [11, 96]. In the northern high-latitude regions, temperatures have risen 0.6 °C per decade over the last 30 years, which is twice as fast as the global average [32]. This is combined with the increase in permafrost degeneration [1] and rapid warming of lake surface water [63]. Under this background, a growing number of studies had started to pay attention to the role of northern freshwaters (lakes and ponds) in CH_4 emissions. The themes are focused on the following:

I. CH_4 emissions from northern thermokarst lakes. Thermokarst lakes can mobilize deeper permafrost stored organic matter, especially for the mineralization of Pleistocene-aged carbon, which may result in positive warming feedback of climate change [76]. However, more research suggests that the permafrost carbon feedback is the synergies of thermokarst lake formation, extension, drainage, and vegetation resume processes (e.g., [22, 87].

II. CH_4 emissions in the seasonally ice-covered lakes. In northern lakes, a significant part of the annual flux occurs

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during the ice-melt period in spring [34, 43, 56] besides the autumn overturn period for dimictic lakes [26]. Hence, the winter ice-covered period is recognized as an accumulation season of CH_4, and knowledge about the importance of lake carbon cycle in the ice-covered period is important to understand present-day conditions and predict the effects of climate change on aquatic systems and the referring feedback effects on the climate [43].

Here, we review the increasing knowledge on CH_4 emissions from northern lakes and provide expectations for future studies.

2 Thermokarst lake dynamics and CH_4 emission feedback

2.1 Permafrost thaw and thermokarst lake formation

Permafrost is defined as ground that remains at or below 0 °C for at least two consecutive years (Permafrost Subcommittee, 1988) and is estimated to occupy about 24% of the northern hemisphere land area, with approximately 70% distributed between 45°N and 67°N [97]. Permafrost warming continues along with the increase in air temperature. Near-surface permafrost in the High Arctic and other very cold areas has warmed by more than 0.5 °C since 2007–2009, and the layer of the ground that thaws in summer, which is usually identified as active layer, has deepened in most areas where permafrost is monitored [1]. Permafrost in the subarctic zone, where the permanently frozen ground is discontinuous, is especially vulnerable to environmental change as it is already close to its thawing point [61]. While even in the Arctic zone of continuous permafrost, an abrupt, large increase in the extent of permafrost degradation has been observed [36].

Thermokarst is the process by which the thawing permafrost ground causes land subsidence, resulting in development of distinctive landforms [46, 76]. Thermokarst formation has important impacts on the hydrology, geomorphology, biogeochemistry, and ecology of the Arctic landscape [8], which will be accelerated under climate change [62]. For example, lakes are formed in the thermokarst landforms following thawing of ice-rich permafrost or melting of massive ground ice and snow [29]. Thermokarst lakes are widespread throughout the Arctic and subarctic lowland areas of western and northern Alaska [64], northern Scandinavia [14], Canada [9], and Siberia [59]. For example, thermokarst lakes comprise approximately 90% of the lakes in the Russian permafrost zone [88], and thermokarst can affect 10–30% of Arctic lowland landscapes in northern Alaska [36].

Thermokarst lakes could bring positive feedbacks to permafrost thaw as permafrost thaw is much deeper under lakes than under terrestrial soils [74, 99]. Thawed water enhances heat flow into the upper permafrost, leading to the thawing of previously frozen soil. If lakes deepen past the maximum depths of winter ice, which are approximately 1.5–2 m in the outer Alaskan Arctic Coastal Plain [2], they maintain a perennially unfrozen pool of liquid water and thawed sediment, which is termed as talik (Fig. 1). The

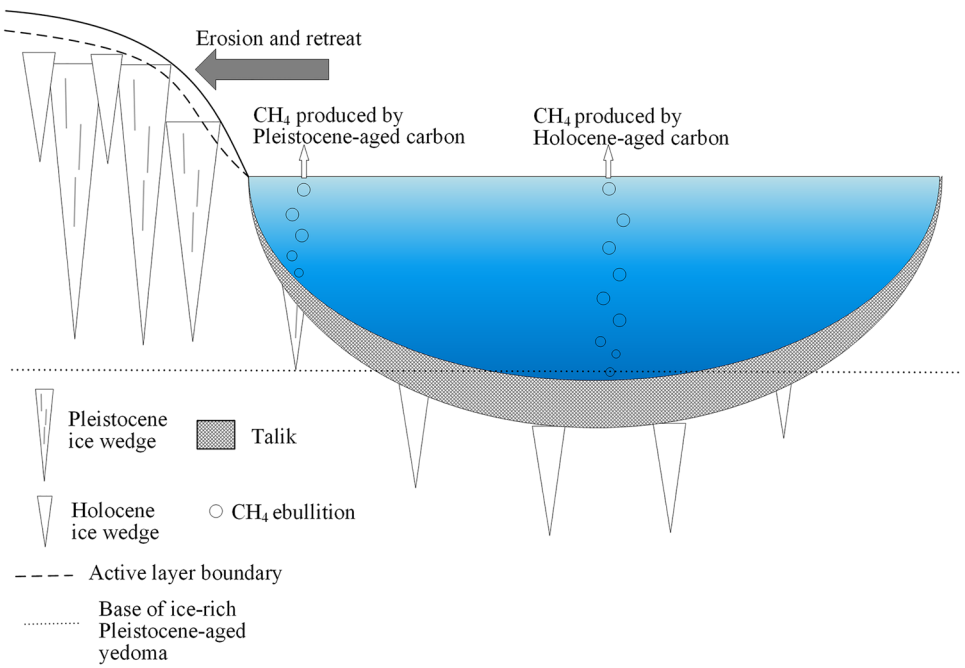

Fig. 1 Schematic showing the thaw-lake CH_4 production by organic carbon of different ages. The supply of H to CH_4 production by Late Pleistocene carbon occurs along thermokarst erosion margins, and the radiocarbon age of CH_4 tend to be younger (e.g., Holocene-aged) toward the lake center. The figure is modified from Brosius et al. [10]

talik can deepen and expose the formerly sequestered organic carbon to microbial activity [2].

Besides of the strong influence on the surface energy balance in permafrost regions [12, 38], thermokarst lakes are also considered to be potential sources of greenhouse gas, which may result in positive warming feedback of climate [76]. Permafrost soils store more carbon than that currently present in the atmosphere and all living biomass combined, which has accumulated for over tens of thousands of years as senesced plant materials are frozen and preserved [97, 98]. Thermokarst lakes can mobilize deeper permafrost stored organic carbon and anaerobic environments in the lake bottoms result in the microbial decomposition of organic matter and CH_4 production and emission [88, 89]. Thermokarst lakes were found to be CH_4 emission hotspots in the northern area [96] and experts assessment revealed that a third to a half of expect climate forcing of permafrost change is from CH_4 [75]. Focusing on the theme of permafrost CH_4 feedback, future studies should answer the following questions: (1) whether massive old carbon (Pleistocene age) stored in the permafrost will be emitted as CH_4, and (2) how future thermokarst lake dynamics (drainage or extension) would affect CH_4 emissions.

2.2 Carbon source for CH_4 emission: old versus young carbon

Regions that remained unglaciated throughout the last glacial maximum accumulated thicker sediments and abundant frozen organic carbon. Among these sediments is one carbon and ice-rich silty loess that termed as yedoma in Siberia, which represents an organic-rich (~ 2% carbon by weight) Pleistocene-aged loess permafrost with a total volumetric ground ice content likely ranges from 65 to 90% [73, 80]. Yedoma covered more than 1 million km^2 of the north plain of Siberia and Central Alaska to an average depth of ~ 20 m [80, 99]. These sediments had carbon contents about 10 to 30 times the amount of carbon generally found in deep, non-permafrost soils. Although yedoma deposits cover only 6% of the global permafrost area, they may store around 20% of all permafrost carbon [80].

Yedoma sediments began melting during the Holocene to form thermokarst lakes, where CH_4 is produced and released primarily by bubbling [88, 99. A study of 40 lakes in Alaska showed that CH_4 emissions from the thermokarst lakes formed in yedoma permafrost soils are much higher than from non-yedoma lakes [78]. Since the high carbon content of Pleistocene-aged permafrost soils, especially for the yedoma region, thermokarst lake was thought to be a canal of the release of old carbon stocks previously stored in permafrost. Experiments showed that the Pleistocene carbon in yedoma soils could lost quite quickly when permafrost thawed [98], and stable isotopes and radiocarbon analyses indicated the distinct $\delta^{13}C$ and ^{14}C-depleted carbon source ($\delta^{13}CH_4 = -70\%$, ^{14}C age 16,500 years) for CH_4 production in North Siberian lakes, suggesting that continued warming of permafrost in the future could lead to accelerated release of ^{14}C-depleted CH_4 (i.e., ancient carbon) from expanding thermokarst lakes [90].

Recently, substrate sources for CH_4 production in the permafrost thaw area have been more precisely investigated. Melt water from permafrost ice serves as H source for CH_4 production in thermokarst lakes. Based on δD_{CH4} measurements, researchers found that Late Pleistocene-aged permafrost ground ice is the dominant H source of CH_4 production in primary (i.e., first-generation) thermokarst lakes, whereas after evolution through lake drainage and reformation, etc. [37], H source of CH_4 in the later generation lakes is primarily from Holocene-aged permafrost ground ice [10]. Besides, the carbon source is also varying in thermokarst lakes. The carbon trajectories for yedoma-region thermokarst basins showed the peak flux of yedoma carbon (e.g., old carbon) at the peak formation of thermokarst lake during deglaciation [93]. An extensive investigation of thermokarst lakes in Alaska, Canada, Sweden, and Siberia revealed that CH_4 emissions from thermokarst lakes are directly proportional to the mass of soil carbon inputs to the lakes from the erosion of thawing permafrost. Moreover, late Pleistocene-aged yedoma soil organic carbon is released in high-flux hotspot seeps located in thermokarst expansion zones, or along boundaries of thawing permafrost, whereas CH_4 from seeps in other zones of yedoma lakes has relatively younger age [92, 94]. Thus, the radiocarbon age of CH_4 is the oldest along thermokarst erosion margins and tends to be younger with increased distance toward the lake center (Fig. 1) [10, 44, 94].

However, a recent study on lakes in Alaska's North Slope found that lake carbon emissions primarily originate from the degradation of recently formed terrestrial carbon, and Pleistocene carbon has only minor contributions [22]. Moreover, they found that the decomposition and emission of ancient carbon are the greatest from the lakes in the coastal plain geology unit, which maintains the combination of warming temperatures, ancient carbon storage, and the development of new or expanding taliks in the thermokarst [22]. Besides, through incubation experiments, Knoblauch et al. [45] pointed out that CH_4 emission in permafrost deposits is not decided by age but instead depends on the organic matter concentration and quality that formed under different past climatic conditions. Recently, a synthesis of ^{14}C measurements from the northern permafrost region showed that the age of CH_4 emitted from lakes depended primarily on the age and quantity

of soil organic carbon in sediments and on the mode of emission [24], since lake ebullition CH_4 was dominated by old carbon especially in high-emission point, while lakes showed much younger diffusive CH_4 fluxes [24, 58]. Therefore, whether relatively fresh and young carbon or ancient permafrost carbon dominates CH_4 production in Arctic lakes may vary among lakes and regions, so future studies must consider permafrost thawing and lake-forming processes, as well as permafrost topographical, geological, and organic matter characteristics.

2.3 Thermokarst drainage and carbon emission

Although increased surface ponding in warming permafrost environments driven by slumping and collapsed terrain features that subsequently fill with water is expected, satellite images of regions rich in thermokarst lakes in many regions show numerous drained and vegetated lake basins, generally exceeding the number and area of extant lakes [29]. The water-level decline and lake shrinkage mainly occur in the southerly zones of discontinuous, sporadic, and isolated permafrost, while the continuous zone is experiencing lake expansion or no significant change [13, 79]. Such differences in observations can be explained if the processes are considered as a continuum, i.e., initial development of thermokarst and lake expansion caused by warming, followed by a reduction in lake surface area to complete subsurface drainage as the permafrost warms and degrades further, allowing hydrological connections between surface and underground flows through portions of unfrozen ground [79]. Lateral drainage caused by lake-shore breaching has also been reported even in the continuous permafrost zone [29]. The dynamics of thaw lakes are markedly influenced by local topography; in low-relief topography, the lake is simulated to expand rapidly and fully drained, while in a high-relief-topography, lake grows slowly and continuously and is only partial drained [44].

Lake drainage causes lake shrinkage and water-level decrease, even return lake area to terrestrial wetland areas, which has a profound impact on the carbon cycle. Previous studies found CH_4 flux in the floodplain of the eastern Siberia decrease rapidly with lower water table, while it serves as a large CO_2 sink [85, 86]. An investigation in Québec, Canada, revealed that permafrost thawing is not primarily accompanied with an increase in thermokarst lakes, but rather with a remarkable increase in vegetation cover [7]. The degradation of permafrost stimulates net carbon storage in the wooded boreal peatlands [84]. Peat accumulation rates were highest in young (50–500 years) drained lake basins, which stores organic carbon that likely offset greenhouse gas release from thermokarst-impacted landscapes [35]. Above all, [93] proved a shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch accompanied by lake drainage and they considered that lake drainage lowers lake water level, slowing thermokarst and stimulating growth of benthic mosses and other plants. In summary, expanding thermokarst lakes can result in carbon evasion by exposing substantial quantities of organic matter to decomposition by microbes, whereas lower near-future CH_4 emissions from these landscapes than previously assumed were predicted due to lake drainage, and the drained or shrinking water masses act as net carbon sinks (at least for CO_2) when vegetation resumes and peat accumulates in old lakebeds [87].

Besides of hydrology, lake drainage could also change the redox condition in the permafrost region. Drained lakes may shift from being a source of CH_4 to being a source of CO_2, whereas CH_4 release decreases due to oxidation or the inhibition of CH_4 production [87]. Nevertheless, considering the greater CH_4 global-warming potential than CO_2, the full magnitude of the climate effect from thermokarst lake drainage depends on the comprehensive estimation of carbon emission and their warming potential. By incubating the permafrost soils in aerobic and anaerobic conditions separately in 15 °C for 500 days, Lee et al. [49] showed that permafrost carbon in a relatively aerobic ecosystems may have a greater effect on climate. The similar method was used by Knoblauch et al. [45] for a 1200 days incubation in 4 °C, which found only 25% of aerobically mineralized carbon was released in the absence of oxygen. Besides, Schuur et al. [76] compared the results from the aerobic permafrost soil incubation [71] with those from another anaerobic incubations [83] and reported 78–85% lower carbon emissions in anaerobic soils than in aerobic ones. More importantly, a long-term incubation (> 12 years) showed that carbon at near-saturated conditions may remain largely immobilized over decades [21]. Moreover, even when accounting for the higher global warming potential of CH_4 relative to CO_2, the ratio of aerobic to anaerobic CO_2–C equivalent (sum of CO_2–C plus CH_4–C expressed as CO_2–C equivalent) was 2.3 times higher in fully aerobic soils than under anaerobic conditions [72]. Hence, a unit of newly thawed permafrost carbon could have a greater impact on climate over a century if it thaws and decomposes within drier, more aerobic soil than an equivalent amount of carbon within waterlogged soil or sediment [76]. In summary, thermokarst lake drainage may induce higher carbon emission as CO_2 and less CH_4 emission in permafrost regions, while the vegetation resume in the original lake area may increase carbon sink. Thus, the landscape changes and their consequences owing to permafrost warming could not be simply defined because changes in permafrost–thermokarst–vegetation should be comprehensively considered.

3 CH_4 emissions in seasonally ice-covered lakes

Climate-sensitive northern lakes and ponds are critical components of CH_4 release [96]. Significant seasonal CH_4 emission has been found in temperate and subtropical lakes because of temperature differences [50, 53, 60], whereas the situation in northern lakes should be different because of the long ice-covered period. Temperate lakes may have abundant CH_4 oxidized or released to the atmosphere during the autumn overturn after CH_4 storage in the summer stagnation period [26], while annual CH_4 emissions in seasonally ice-covered northern dimictic lakes are characterized by two cycles of CH_4 loss and buildup, namely CH_4 loss during spring and autumn overturn with interim periods of buildup during summer stratification and under winter ice cover [56]. The winter ecology may be more active and play a more important role than expected; it can even influence the subsequent summer nutrient variables and biomass [30]. Conversely, reduced ice-cover dates in northern lakes [52] highlight an urgent need for research focused on under-ice CH_4 dynamics and the contribution to annual emission.

3.1 CH_4 accumulation under ice and spring emission

In boreal, Arctic, and many mountainous regions, lakes are covered by ice for a major part of the year. In lakes, CH_4 is typically produced in anoxic bottom sediments by methanogenic microbes and can be released to the atmosphere by diffusion, vascular transport through aquatic plants, or ebullition (bubbling) in the open-water season [3]. While in most cases, the atmospheric exchange is limited when the ice on, and gases are trapped in the ice and underlying water (Fig. 2), with a little part escape through openings in the ice owing to ice cracks caused by increased pressure and/or warm waters from inflows and frequent CH_4 bubbling [88], as well as from emergent vegetation through the ice [48]. Water-dissolved CH_4 that diffuses from the sediment accumulates in the water column beneath the ice, as well as the ebullition CH_4. In the early winter when ice is forming, bubbles are encapsulated by downward-growing lake ice, and then bubbles are trapped beneath the ice wall with a part dissolving into the water column [90]. If CH_4 escaped oxidation under ice and during the ice out, CH_4 accumulation under the ice could result in gas "storage," and large diffusion emissions occur when the ice melts in spring. This emission is often enhanced by full or partial lake overturn [43, 56, 81]. Overturn can cause oxygenation, potentially removing CH_4 [28, 68], but it can also efficiently transport gases from the lake bottom throughout the water column onto the lake surface before diffusing to the atmosphere [26]. Consequently, CH_4 trapped during winter can be efficiently released during spring when ice melts and water mixes.

Numerous studies have pointed out the importance of CH_4 accumulation under ice and emission during spring ice thaw, but their contribution to annual CH_4 emission

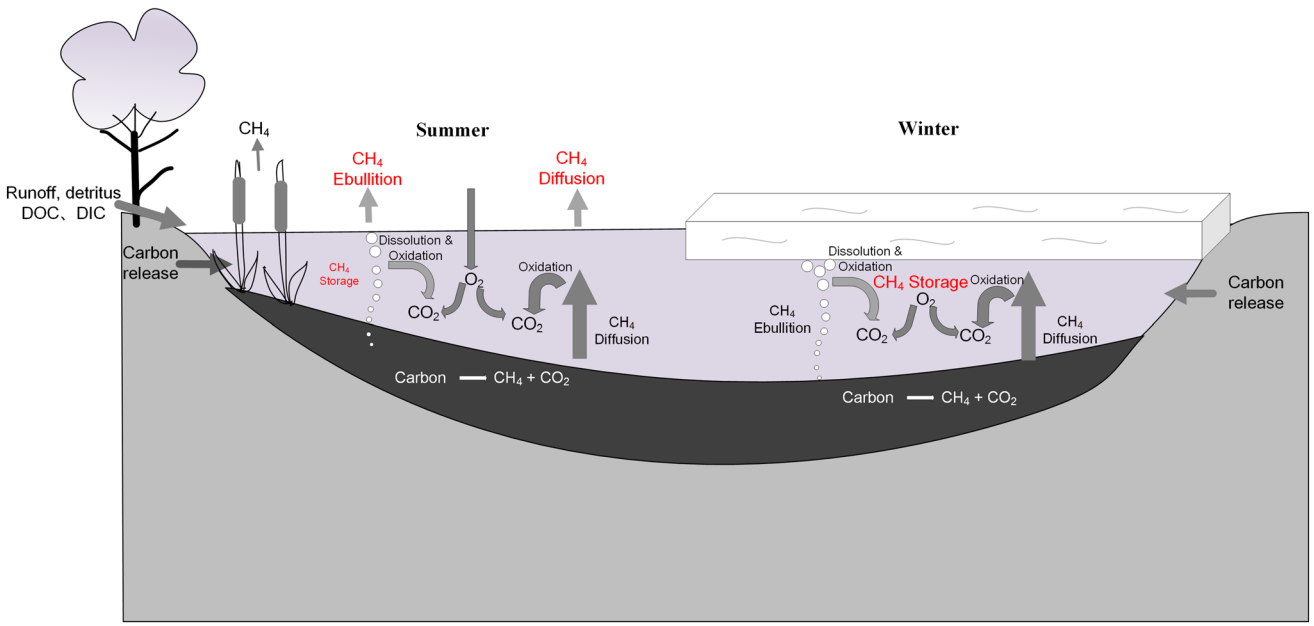

Fig. 2 Methane dynamics in northern seasonally ice-covered lakes during the summer and winter

remains uncertain for lakes on a regional or larger spatial scale. Thus, more studies covering the whole year and accounting for CH_4 emission during the ice-out and autumnal mixing period are needed to better assess the contribution of northern lakes to the global carbon cycle, and their sensitivity to climate change. In the present work, we compiled published studies inferring quantified CH_4 emission for both the ice-melt and open-water periods. The method used is similar to that in Denfeld et al. [18] but with supplementation of newly published data. Ice melt refers to springtime when the start of ice thaw until complete ice off. Open-water time is ice free that includes the summer and the possible autumn turnover period. We obtained data for 261 lakes with 265 data points (Table 1 and Supporting Information Table S1). Previous studies estimated the spring efflux by using bubble traps under the ice or floating chambers, as well as by sampling CH_4 dissolved in the lake water right before and after ice melt or by monitoring CH_4 fluxes with eddy covariance [34]. Just like that in Denfeld et al. [18], we also calculated the percentage contribution of ice-melt flux to annual CH_4 emission to reduce the uncertainty between different methods used to estimate CH_4 fluxes. Results show that the ice-melt emission contribution ranges from 0 to 100%, with an average of 28% and a median of 18%. There were 23% observations of ice-melt CH_4 emission that had annual emission contribution more than 50%. CH_4 ebullition is considered only in limited studies, and the estimated ice-melt CH_4 emission contribution that includes ebullition is slightly lower or higher than the estimates that do not include ebullition (the differences were lower than 10%) depending on the influence of ebullition on CH_4 flux in ice-melt and ice-free periods (Table S1).

Studies about ice-melt lake CH_4 emission have been primarily conducted in Finland and Sweden, Siberia, and northern North America (Table 1). Higher CH_4 emission occurs in lakes located in Alaska, which has yedoma-sediment distribution [99] and permafrost-affected regions in Western Siberia [77]. Moreover, the ice-melt period CH_4 emission contribution has no obvious difference among various study areas, except the high value in the Minnesota, USA, although the limited measurement in this area precludes further comparison (Table 1).

It should be noted that the spring ice-melt CH_4 emission may be underestimated for the following seasons. Firstly, the CH_4 ebullition through open hole in winter lake ice and the ice-bubble storage [91] are tend to be neglected when using quantified carbon gas storage before and after ice-out to estimate the spring efflux [34, 43]. Secondly, the unfreezing or ice-out period is brief for most northern lakes, during which considerable amounts of gas are emitted rapidly, while at this time the lakes are inaccessible due to the floating ice. Hence, it is urgent to develop better methods to capture this critical and challenging period [66].

3.2 The possible influencing factors for ice-melt CH_4 emission

3.2.1 Ice-melt CH_4 emission versus lake area and depth

Previous studies estimating spring efflux have found the relationships of ice-melt CH_4 flux with physical lake characteristics. For example, Michmerhuizen et al. [56] considered that CH_4 emission per unit area decreases with increased lake area. More studies have focused on ice-melt carbon emission versus lake depth. The study on three lakes in northern Sweden by Jansen et al. [34] concluded that spring CH_4 emission contribution is higher in deep lakes than in shallow ones. However, the study of Juutinen et al. [40] involving 207 Finnish lakes suggested that very humic, shallow lakes have more CH_4 storage in late winter–spring period than in summer–autumn. Recently, Prėskienis et al. [66] pointed out that water body morphology could strongly affect the seasonal patterns of CH_4 flux through the effect on the mixing regime.

Here, we examined the relationships between ice-melt CH_4 emission flux/ contribution and lake area/ maximum depth, and found relatively high spring ice-melt CH_4 emission from small and shallow lakes (Fig. 3). Similar results

Table 1 Northern lakes' CH_4 emissions at ice-melt and ice-free periods from different study areas expressed as average ± standard deviation, and the percentage contribution of ice-melt CH_4 emission to annual emission expressed as mean and median values. The ebullition flux is not included

Lake number	Study area	Ice melt (mmol m^{-2})	Ice free (mmol m^{-2})	Contribution (%)	References
16	Alaska, USA	364.1 ± 934.5	1423.8 ± 3666.5	16 (median = 14)	[65, 78]
10	Northern Canada	113.3 ± 136.5	266.4 ± 377.5	29 (median = 18)	[47, 95, 16, 55]
2	Minnesota, USA	240 ± 28.3	110 ± 70.7	70	[81]
29	Western Siberia	511.0 ± 598.1	3258.3 ± 3203.1	19 (median = 17)	[77]
204	Finland & Sweden	90.2 ± 104.3	134.3 ± 151.2	29 (median = 18)	[6, 18, 19, 31, 33, 34, 39–43, 48, 57]

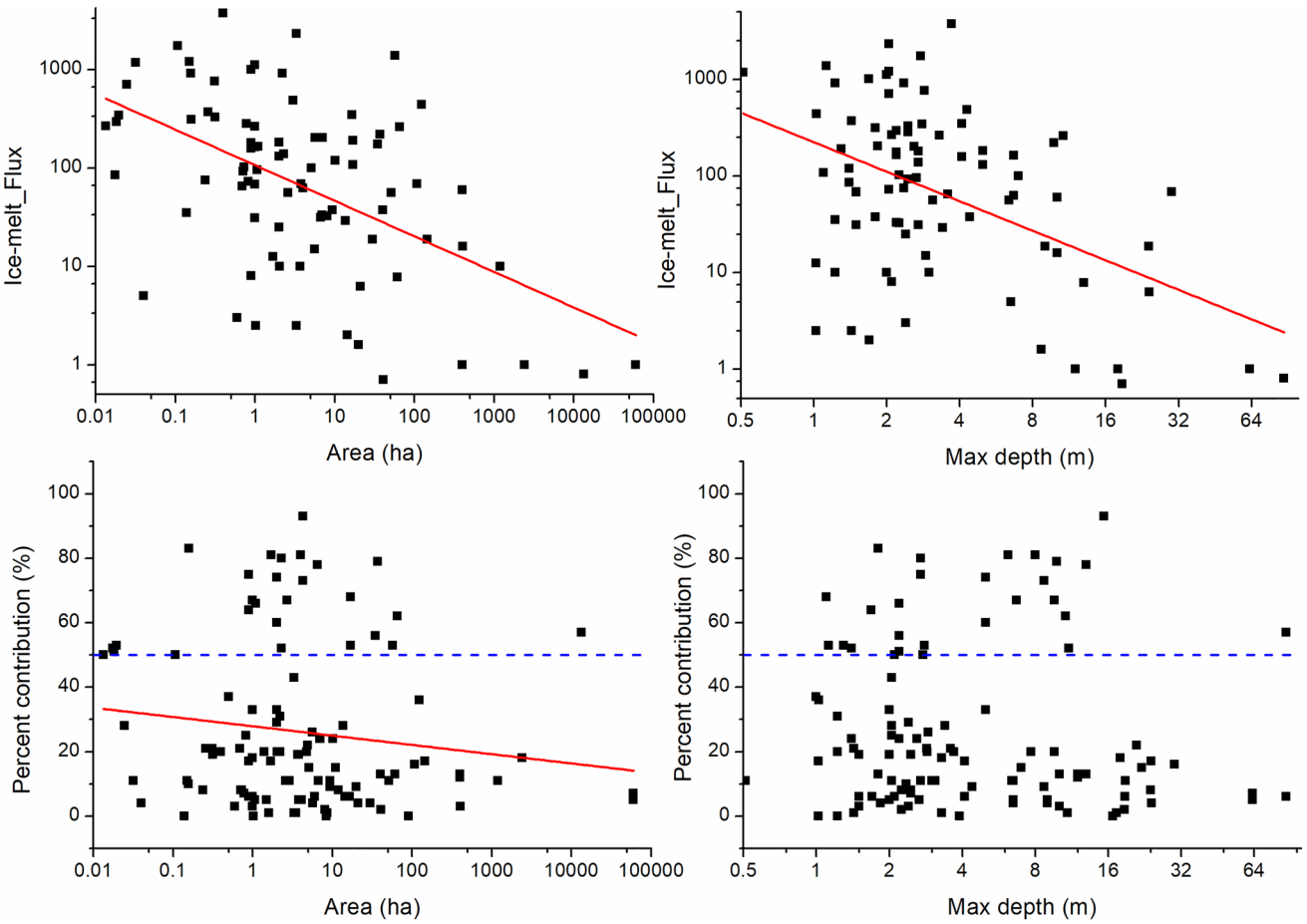

Fig. 3 Ice-melt CH_4 emission flux (mmol m^{-2}) and the percentage contribution in relation to lake area and maximum depth. Red lines are linear fits of all data; blue dash lines equal to 50% contribution. Note logarithmic axes

were reported for CH_4 fluxes in the ice-free period in Wik et al. [96]. While different from the results in Wik et al. [96] that found weaker effect of lake area on CH_4 fluxes than maximum depth, our results showed slightly greater effect of lake area (general linear model, $R^2 = 0.29$) than maximum depth (general linear model, $R^2 = 0.23$) on ice-melt CH_4 fluxes. This finding is consistent with the discussion in Denfeld et al. [18] that small lakes often have incomplete autumn mixing and faster ice development, due to the characteristics of well shelter from the wind and rapid cooling, which may result in high CH_4 concentrations under ice. However, we found weak or no correlation between the contribution percentage and lake characteristics (for the lake area, general linear model, $R^2 = 0.01$) (Fig. 3). This result may be explained by the similar effects of lake morphology on CH_4 fluxes in the spring ice-melt and ice-free periods. Figure 3 also shows that the over 50% ice-melt CH_4 emission contributions are mostly within the areas of 0.1–100 ha and maximum depths of 1–10 m, indicating the potential of higher spring CH_4 emission contribution in shallow and small lakes. However, these results also suggest the existence of other factors that influence ice-melt CH_4 emission.

3.2.2 Ice-melt CH_4 emission versus CH_4 oxidation

The under-ice accumulation of CH_4 during ice cover within a lake is influenced by the rates of CH_4 production and oxidation. CH_4 oxidation is proved to occur at under ice low temperatures [67] and methanotrophs are highly active in ice-covered lake water [41]. The presence of ice impeded CH_4 diffusion and ebullition, resulting in CH_4 accumulation under ice. Hence, different from the CH_4 limitation in summer, aerobic CH_4 oxidation is thought to be primarily controlled by the redox condition in the winter [54]. The under-ice water oxygen concentration is related to respiration and photosynthesis, as well as water-column volume. Hence, CH_4 oxidation during ice cover may vary among shallow and deep lakes; the prevailing low oxygen concentration in the shallow lakes may induce to CH_4 oversaturation under ice. For example, Phelps et al. [65] explored several shallow lakes and found the decline of

oxygen levels after ice cover combined with increased CH_4 levels following lake anoxia, and they considered that the marked increase in CH_4 under the ice is due more to decreased rates of CH_4 oxidation than to increased rates of CH_4 production. In contrast, Striegl and Michmerhuizen [81] examined two larger and deeper lakes (~ 10 m maximum depth), and found that complete anoxia does not commonly occur in the water column; CH_4 oxidation potential is continuously present all the time.

Apart from interior processes under ice, the water-column redox condition is also influenced by the lake-mixing event. A complete spring turnover of the water column brings oxygen to the hypolimnion and may result in an oxic condition in the hypolimnion during summer. By contrast, short or incomplete spring turnover may accompany the anoxic condition in the hypolimnion in the summer [41]. Similarly, the autumn turnover could probably influence the redox condition during winter ice cover, which is directly linked to CH_4 oxidation and accumulation under ice. The study of Kankaala et al. [41] in a small, shallow lake that has incomplete spring water-column mixing revealed that the total CH_4 consumption in the water column during the winter ice-covered period is higher than the efflux to the atmosphere in spring, and that 79% CH_4 is consumed in the water column on an annual scale. Although water-column mixing upon ice melt tends to release CH_4 accumulated in the bottom waters directly into the atmosphere, increased potential of CH_4 oxidation in the water column could occur when water-column mixing occurs before the ice melt, but complete mixing is more commonly observed only at the time of ice melt [18].

Winter CH_4 oxidation seems to play a more important role in lakes with high CH_4 ebullition from the sediment because the dissolution of bubbles that accumulated under the ice increases the potential of CH_4 oxidation. Model estimation has shown that 80 percent of CH_4 in bubbles trapped by ice dissolves into the lake water under the ice, and about half of that is oxidized [28]. The recent study by Elder et al. [23] using the measurement of dissolved gas concentrations and their ^{14}C and ^{13}C isotopes showed that the winter ice forced 50% ebullition CH_4 to be oxidized by the end of winter, and the other half is accumulated in the dissolved CH_4 pool under ice. Apart from dissolution, CH_4 trapped in bubbles could also be released through diffusion, contributing to CH_4 accumulation in the ice–water interface, where significant CH_4 oxidation may be fueled [67]. However, an incubation experiment for under-ice lake water revealed that elevated CH_4 concentration in the oxic lake water could not sufficiently activate CH_4 oxidation in some lakes with low phosphate concentrations, suggesting that CH_4 oxidation does not depend on CH_4 or oxygen availability in these lakes. While CH_4 oxidation was restricted to three lakes, where the phosphate concentrations were highest, they speculated that available phosphate may potentially provide sufficient phosphorus to sustain fast-growing heterotrophs and slow-growing methanotrophs because all organisms require phosphorus for cell division, energy transformations, and cell maintenance [17]. The relationship between methanotrophs abundance and phosphate concentration was also found in other lakes [69].

In summary, CH_4 oxidation under ice or during the ice melt could significantly decrease CH_4 emission to the air, which depends on CH_4 production, oxygen available, the extent of lake mixing, as well as the nutrients that may influence the methanotrophs. Besides, an increasing number of studies have confirmed cascading effects of lake ecology in the ice-cover and ice-free periods. For example, the dissolved oxygen concentration and thermodynamic could be influenced by former lake turnover [63], and the ice conditions, for instance, duration and thickness, have also been observed to affect the phytoplankton community in the subsequent ice-free seasons [20, 27]. Nevertheless, we only have ambiguous knowledge on some important questions about CH_4 and oxygen dynamics under ice, such as how autumn overturn affect winter oxygen concentration and how reduced ice-cover duration affect CH_4 production in the next ice-free season.

3.2.3 Ice-melt CH_4 emission versus hydrological carbon input

Apart from autochthonous carbon by photosynthesis, a large amount of carbon in the lake is from river inflow, that is allochthonous carbon. The evidence shows that global change in northern regions leads to reduced primary productivity, resulting in increased proportion of allochthonous dissolved organic matter supply to northern lakes [15]. The hydrological patterns may influence carbon loading to lakes [82] and carbon evasion from the lakes. The result of a process-oriented lake biogeochemical model suggests that increasing organic matter input from the catchment increases future CH_4 emission in lakes [5]. Moreover, rivers could also directly bring dissolved carbon into the lake, especially for dissolved CO_2 in groundwater and surface water, whereas the input of external source CH_4 is thought to account for a smaller proportion than CH_4 produced by anaerobic decomposition in lake sediment [81]. However, this viewpoint seems to be challenged when an extreme rain event occurs. After heavy rain, CH_4 concentration in the metalimnion and epilimnion increases and exceeds the CH_4 concentration in deeper water when the water column is stratified, indicating that CH_4 may be transported from the external [51, 57].

Except for runoff, other factors such as atmospheric pressure and water-column stratification, which could

influence lake surface CH_4 concentration in heavy rain, have rarely been discussed. These factors are important because heavy rain accompanied with wind may break up the long-term temperature stratification, resulting in the come-up of bottom CH_4. External dissolved organic carbon and CH_4 import can also contribute to ice-melt CH_4 emission. Abundant carbon received by groundwater and surface water input maintains methanogenesis during the ice-covered wintertime, inducing large lake CH_4 storage in the late winter and emission to the atmosphere immediately following ice melt [81]. Denfeld et al. [19] found higher CH_4 concentrations in surface waters during sporadic ice-melt events over winter and considered that hydrological inputs should be a key driver of below-ice CH_4 in the lake. Meanwhile, the effect of external CH_4 or carbon input on CH_4 emission at ice melt may depend on soil and landscape features, for example, whether the surrounding basin can export organic matter or CH_4 into the lake.

4 Summary

We reviewed research on CH_4 emission in northern thermokarst and seasonally ice-covered lakes. These topics are associated with a sense of urgency and societal need under observed and modeled permafrost warming, near-surface permafrost degeneration, increased hydrological activity of thermokarst lakes, winter warming, and reduced ice-cover duration over the past decades [52, 76], 94]. We found the following key issues that need to be addressed to enhance our understanding of CH_4 emission contributed by northern lakes.

(1) Ancient carbon stored in permafrost could be substantially emitted as carbon gas under climate warming. To determine the potential of ancient carbon emission, future research in the northern permafrost region must consider the thermokarst and lake-forming processes, the variable geological conditions, and the carbon dynamics of thermokarst lakes.
(2) The evolution trends of thermokarst lakes in continuous and discontinuous permafrost regions, such as the thermokarst lake expansion or drainage, and the corresponding influence on CH_4 emission and feedback to future climate change should be explored.
(3) The cascading effects of lake ecology in the ice-cover and ice-free periods, and the influence on CH_4 emission under climate change are observed.
(4) Large-scale studies on lake CH_4 dynamics under ice and comparison with mechanisms in the ice-free period (e.g., CH_4 production and CH_4 oxidation related to water temperature, redox condition, and nutrients) should be conducted.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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