



Exceptional summer warming leads to contrasting outcomes for methane cycling in small Arctic lakes of Greenland

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Abstract. In thermally stratified lakes, the greatest annual methane emissions typically occur during thermal overturn events. In July of 2012, Greenland experienced significant warming that resulted in substantial melting of the Greenland Ice Sheet and enhanced runoff events. This unusual climate phenomenon provided an opportunity to examine the effects of short-term natural heating on lake thermal structure and methane dynamics and compare these observations with those from the following year, when temperatures were normal. Here, we focus on methane concentrations within the water column of five adjacent small lakes on the ice-free margin of southwestern Greenland under open-water and ice-covered conditions from 2012–2014. Enhanced warming of the epilimnion in the lakes under open-water conditions in 2012 led to strong thermal stability and the development of anoxic hypolimnia in each of the lakes. As a result, during open-water conditions, mean dissolved methane concentrations in the water column were significantly ($p < 0.0001$) greater in 2012 than in 2013. In all of the lakes, mean methane concentrations under ice-covered conditions were significantly ($p < 0.0001$) greater than under open-water conditions, suggesting spring overturn is currently the largest annual methane flux to the atmosphere. As the climate continues to warm, shorter ice cover durations are expected, which may reduce the winter inventory of methane and lead to a decrease in total methane flux during ice melt. Under open-water conditions, greater heat income and warming of lake surface waters will lead to increased thermal stratification and hypolimnetic anoxia, which will consequently result in increased water column inventories of methane. This stored methane will be susceptible to emissions during fall over-

turn, which may result in a shift in greatest annual efflux of methane from spring melt to fall overturn. The results of this study suggest that interannual variation in ground-level air temperatures may be the primary driver of changes in methane dynamics because it controls both the duration of ice cover and the strength of thermal stratification.

1 Introduction

Methane (CH₄) emissions from freshwater environments are expected to increase with warming climates (Juutinen et al., 2009; Yvon-Durocher et al., 2011, 2014; Tan and Zhuang 2015a, b) but quantitative modeled projections of emissions are poorly constrained (Bastviken et al., 2011; Rasilo et al., 2015; Sepulveda-Jauregui et al., 2015; Tan et al., 2015). Observations of seasonal and annual lake CH₄ dynamics in the Arctic are necessary to define source estimates in models and understand the impact warming may have on greenhouse gas emissions. Currently, in the Arctic, small lakes (surface area < 10 km²) are abundant (Downing, 2010; Downing et al., 2006) and emit substantially more CH₄ per unit area than larger lakes (Bastviken et al., 2004; Cole et al., 2007; Juutinen et al., 2009; Wik et al., 2016), and seasonal variability in CH₄ emissions are influenced by energy input and organic carbon availability (Tan et al., 2015). However, climate change will lead to variations in heat balance, temperature profiles, and vertical mixing in lakes (Jankowski et al., 2006; MacIntyre et al., 2009; Hinkel et al., 2012; Butcher et al., 2015), causing many variations to both lake structure (Livingstone 2003; Coats et al., 2006) and CH₄ dynamics.

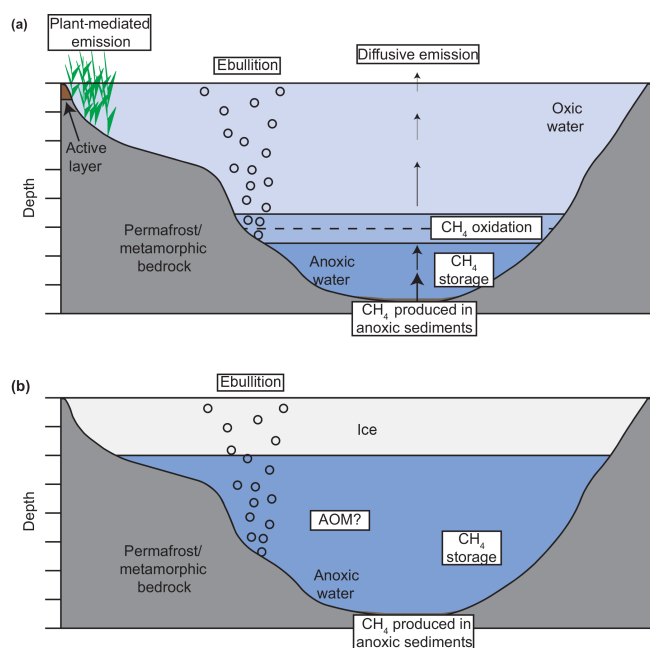


Figure 1. Methane emission pathways and dynamics in a bedrock controlled thermokarst lacustrine system under both open-water and ice-covered conditions.

Microbial production of CH₄ by methanogens is dependent upon anoxia, temperature, and the amount and quality of organic carbon substrates (Liikanen et al., 2003; Kankaala et al., 2006; Duc et al., 2010; Borrel et al., 2011). A large proportion of the CH₄ produced in lakes is consumed by aerobic or anaerobic oxidation (Frenzel et al., 1990; Bastviken et al., 2002; Kankaala et al., 2007; Dzyuban, 2010; Martinez-Cruz et al., 2015). Aerobic microbial oxidation of methane (MOx) depends on the availability of both CH₄ and O₂, wherein higher MOx rates are usually found at the oxic–anoxic interface, where both CH₄ and O₂ are present in high concentrations (Bastviken et al., 2002; Dzyuban, 2010). Excess CH₄ that escapes MOx and reaches the upper mixed layer of the water column (epilimnion) is available for emission to the atmosphere by molecular diffusion under open-water conditions. Emission by ebullition and plants results in a direct flux of CH₄ to the atmosphere with limited oxidation in the water column (Keppler et al., 2006; Walter et al., 2006, 2007; Nisbet et al., 2009; Wik et al., 2013; Greene et al., 2014).

In lakes, the amounts of CH₄ in the water column (hereafter referred to as inventory) and CH₄ available for diffusive emissions (hereafter referred to as active CH₄) are strongly influenced by thermal stratification and seasonal overturns (Kankaala et al., 2007; López Bellido et al., 2009; Encinas Fernandez et al., 2014). Arctic lakes that are deep enough to stratify are usually dimictic (spring and fall turnover) or cold monomictic (spring turnover) in areas without perennial ice cover. During thermal stratification, a lack of mixing between the epilimnion and anoxic hypolimnion sup-

presses gas transfer between these layers, allowing CH₄ to accumulate below the oxycline (hereafter referred to as storage; Fig. 1; Bastviken et al., 2004; Sepulveda-Jauregui et al., 2015). During mixing from fall turnover, all CH₄ previously stored in the hypolimnion is susceptible to MOx and/or diffusion (Encinas Fernandez et al., 2014). Under ice cover, CH₄ can accumulate and is either stored under ice or within the ice (Fig. 1; Walter et al., 2006; Walter Anthony et al., 2012; Sepulveda-Jauregui et al., 2015). In spring, the break-up of the ice and mixing allows stored CH₄ to be oxidized or emitted from the system through diffusion or ebullition (Juutinen et al., 2009; López Bellido et al., 2009; Karlsson et al., 2013; Greene et al., 2014; Jammot et al., 2015). Emissions of stored CH₄ during overturn events accounts for up to 40 % of the total annual flux in lakes globally (Michmerhuizen et al., 1996; Juutinen et al., 2009; López Bellido et al., 2009; Encinas Fernandez et al., 2014; Jammot et al., 2015).

Over the last three decades, increasing atmospheric temperatures have resulted in increased lake temperatures and decreases in ice cover (Weyhenmeyer et al., 2011; Kraemer et al., 2015). Warming of surface waters will lead to increased thermal stratification and hypolimnetic anoxia, which should cause higher inventories of dissolved CH₄ stored in the hypolimnion of the water column. In addition to changes to thermal structure, warming and thawing of permafrost in the Arctic may allow organic carbon, nutrients, and ions that were previously frozen in sediments to be transported into aquatic systems and become available for microbial utilization (Kokelj et al., 2009; Loughheed et al., 2011; Weyhenmeyer et al., 2011). Experimental laboratory incubation studies have also demonstrated that microbial CH₄ production significantly increases with increased temperature (Duc et al., 2010; Lofton et al., 2013; Fuchs et al., 2016).

On the ice-free margin of southwestern Greenland, hundreds of thousands of Holocene lakes perched on continuous permafrost cover the landscape (Anderson et al., 2001; Anderson and Stedmon, 2007; Jorgensen and Andreassen, 2007). As a result of amplified warming in the Arctic over the past 20 years (IPCC, 2013), Greenland has experienced significant mass loss of the Greenland Ice Sheet (GIS; Nghiem et al., 2012; van As et al., 2012; Hall et al., 2013; Hanna et al., 2013, 2014). Despite the abundance of lakes on the ice-free margin of Greenland and intense changes to the landscape as the result of warming, there are only a few published studies that have measured CH₄ in Greenlandic lakes (Walter Anthony et al., 2012; Webster et al., 2015; Cadieux et al., 2016; Goldman et al., 2016).

The anomalously warm summer in Greenland 2012, which resulted in substantial surface melt of the GIS (Nghiem et al., 2012; Hanna et al., 2014), provides an opportunity to examine the effects of surface water heating on CH₄ dynamics in lakes. In this study, we quantify the depth inventories of CH₄ under both open-water and ice-covered conditions for five adjacent small lakes on the ice-free margin of southwestern Greenland from 2012 to 2014. In doing so, we are able to

Table 1. Morphometrics and median physicochemical characteristics of lakes under open-water conditions in 2012.

	Z_{\max} (m)	Fetch (m)	Surface area (ha)	Volume (m ³)	pH	Specific conductivity (mS cm ⁻¹ °C)	DOC (mg L ⁻¹)
EVV Upper*	5.5	68	0.22	5200	7.0 (11)	0.7 (11)	38.7 (4)
EVV Lower	4.5	180	1.5	31 000	8.9 (10)	1.2 (10)	38.4 (2)
Teardrop*	5.25	160	0.97	34 000	9.2 (11)	4.3 (11)	92.0 (4)
Potentilla*	8.0	280	1.6	160 000	7.2 (15)	0.4 (15)	11.4 (3)
South Twin	5.5	310	3.1	120 000	7.9 (11)	4.0 (11)	20.5 (3)

Sample size is in parentheses. * Can also be found in Cadieux et al. (2016).

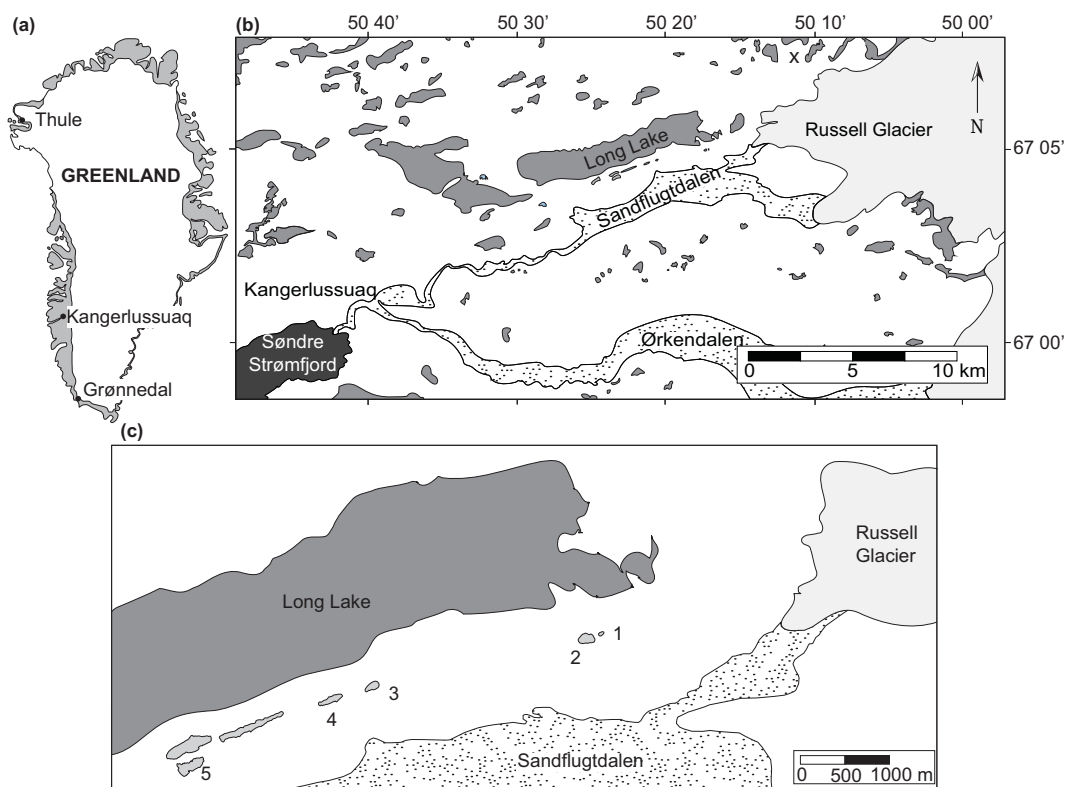


Figure 2. (a) Greenland, showing Kangerlussuaq. (b) Regional map of Kangerlussuaq and the inland ice margin, including Sandflugtdalen and Ørkendalen, which are two major proglacial valley sandur systems. X marks the location of the Geological Survey of Denmark and Greenland (GEUS) weather station. (c) Study area map of lakes relative to the Russell Glacier, Long Lake, and Sandflugtdalen sandur. (1) EVV Upper lake, (2) EVV Lower lake, (3) Teardrop lake, (4) Potentilla lake, and (5) South Twin lake. Figure is modified from Cadieux et al. (2016).

look at differences in CH₄ spatially among the lakes, seasonally by comparing open-water conditions to ice-covered conditions, and annually. The study lakes are ice-covered for 9–10 months of the year, leading us to predict that methane concentrations would be significantly greater under ice-covered conditions as opposed to open-water conditions. Under open-water conditions, we hypothesized that warmer conditions in the summer of 2012 would lead to increased thermal stratification and significantly greater CH₄ concentrations under open-water conditions than in 2013.

2 Study area

The study area lies between the village of Kangerlussuaq, Greenland, at the head of Søndre Strømfjord and the active terminus of the Russell Glacier (Fig. 2). The region has continuous permafrost extending from 50 cm below the surface to 130 m at Kangerlussuaq and 500 m at the ice sheet (Jorgensen and Andreasen, 2007). Soils in the region are not well developed, composed of till and glaciofluvial deposits (Van Tatenhove and Olesen, 1994). Precipitation in the Kangerlus-

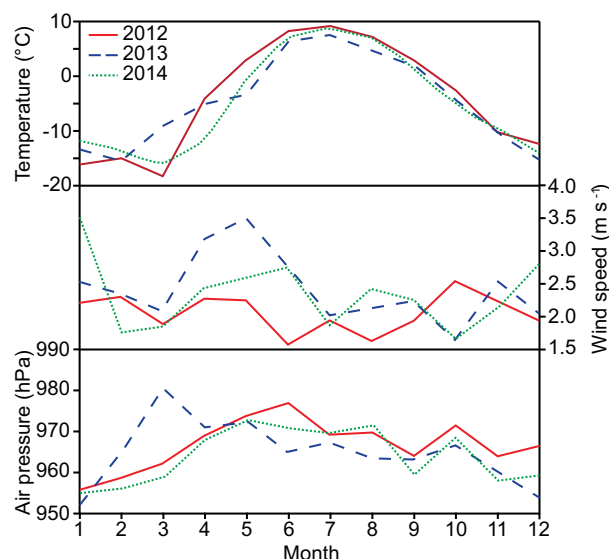


Figure 3. Mean monthly temperature, wind speed, and air pressure for Kangerlussuaq from 2012 (red solid line), 2013 (blue dashed line) and 2014 (green dotted line). Data from the Program for Monitoring of the Greenland Ice Sheet (PROMICE) and the Greenland Analog Project (GAP) were provided by the Geological Survey of Denmark and Greenland at <http://www.promice.dk>.

suaq region is low, with annual precipitation $< 150 \text{ mm yr}^{-1}$. Dwarf shrubs (*Salix*, *Vaccinium*, and *Betula*) and graminoids (*Carex* and *Calamagrostis*) dominate the tundra vegetation in the region.

This paper focuses on five small lakes (surface area $< 3 \text{ ha}$, maximum depth $< 8 \text{ m}$), with a range of different morphometries and aquatic chemistries (Table 1). The lake names used herein (EVV Upper Lake, EVV Lower Lake, Teardrop Lake, Potentilla Lake, and South Twin Lake) are informal, based on local surficial features. The study lakes are part of a series of lakes within a narrow valley overlying a structural shear zone extending from the Russell Glacier to the Søndre Strømfjord (Fig. 2). The lakes are, at most, 6 km apart and are subject to the same climatic forcing. All lakes in the study are dimictic, exhibiting ice cover from late October to early June. Currently the study lakes are all hydrologically closed basins, with no active inflow or outflow channels observed from 2011 to 2014. Groundwater seepage into the lakes is assumed to be limited due to continuous permafrost.

In summer 2012, a blocking high-pressure system formed a heat dome over Greenland, leading to widespread surface melting of the GIS (Hall et al., 2013; Hanna et al., 2014; Nghiem et al., 2012). As a result, this circulation pattern produced mean daily ground-level air temperatures in Kangerlussuaq that were the highest on record (Hanna et al., 2014). Weather data from a local Geological Survey of Denmark and Greenland (GEUS) station (van As et al., 2011; Fig. 2) showed that mean monthly ground-level temperatures for June–August in 2012 were $\sim 2^\circ\text{C}$ higher than in

2013 (Fig. 3). Correspondingly, mean air pressure from May to August of 2012 was higher than in 2013 (Fig. 3). Mean monthly wind speeds in the Kangerlussuaq region ranged from 1.52 in June 2012 to 3.51 m s^{-1} in May of 2013 (Fig. 3). At the Kangerlussuaq airport, average temperatures from May to August of 2013 were within the range observed from 1996 to 2011, suggesting 2013 weather is typical for the region (data retrieved from www.weatherunderground.com).

3 Methods

3.1 Sample collection and water chemistry analysis

Lakes were sampled in July of 2012 and 2013 and in April of 2013 and 2014 in order to measure both summer and winter stratification. Hereafter, July samplings will be referred to as open water and April samplings as ice-covered. Only EVV Upper lake and Potentilla lake were sampled during all four sampling dates. All samples and measurements were taken at a location above maximum water depth (Z_{max}). Under open-water conditions, samples and measurements were collected using an inflatable Alpaca raft (Anchorage, AK, USA), and under ice-covered conditions, when each lake was covered by $\sim 2 \text{ m}$ of ice, a hole ($\sim 30 \text{ cm}$ in diameter) was augured through the ice in order to sample. Temperature (T , $^\circ\text{C}$), pH, dissolved oxygen (DO, mg L^{-1}), oxidation-reduction potential (ORP, mV) and specific conductivity (mS cm^{-1}) were measured using a YSI 6093 data sonde (Yellow Springs Inc., Yellow Springs, OH, USA) deployed at vertical intervals of 0.5 m depth.

Water for chemical analysis was collected from the water column using a Narrow Diameter SupernovaTM electronic submersible pump. Samples were frozen, and transported to Indiana University, where all chemical analyses were conducted. Dissolved organic carbon (DOC) was analyzed from filtered samples that were acidified using hydrochloric acid (HCl), and analyzed via high-temperature oxidation using a Shimadzu total organic carbon analyzer following methods described in Oviedo-Vargas et al. (2013) (corresponding method detection limit (MDL) $= 0.15 \text{ mg C L}^{-1}$). Concentrations of ions were analyzed using a Dionex ICS 2000 ion chromatograph using a CS12A analytical cation column, CSRS 300 4 mm suppressor, and 20 mM methanesulfonic acid eluent for cations and AS11-HC analytical anion column, ASRS 4 mm suppressor, and 30 mM potassium hydroxide eluent for anions.

3.2 CH_4 collection

With the exception of Potentilla lake under ice-covered conditions in 2014, water samples for dissolved CH_4 in the water column were collected using an electronic submersible pump. Samples were collected at $0.25\text{--}1.0 \text{ m}$ intervals through the water column and were immediately stripped in the field using a headspace-equilibrium technique

(Westendorp, 1985) to extract CH_4 from water. At each depth interval, 500 mL of water was collected into a 1 L Erlenmeyer flask and vigorously shaken for 1 min. Headspace gas in the flask was displaced into a Cali-5-Bond bag using surficial lake water (Cadieux et al., 2016). Under ice-covered conditions in 2014, dissolved CH_4 in Potentilla lake was collected using a string of passive diffusion bags (PDBs) deployed in the lake for 5 days in order to obtain a high-resolution profile of dissolved CH_4 in the water column (Goldman et al., 2016). The PDBs are composed of a polyethylene membrane with a protective plastic mesh and are commercially available from EON Products Inc. (Georgia, USA). After 5 days, PDBs were retrieved from the lake and dissolved gas was sampled immediately in the field using the equilibrium gas stripping method described above. Further details regarding PDB methodology, preparation, and applicability can be found in Goldman et al. (2016).

Profundal sediment samples were taken from Z_{max} of each lake during ice-covered conditions and open-water conditions in 2013 using a Wildco push-coring device. Cores were transferred back to the laboratory at Kangerlussuaq International Science Support (KISS) facility and immediately refrigerated at 4 °C and processed within 24 h of collection. Dissolved gas in the sediment was sampled using an equilibrium gas stripping method similar to that used for the water column CH_4 . Sediment cores were subsectioned into 6–10 cm intervals and each subsection was put into a 8 L Nalgene bottle with zero- CH_4 water to create 2 L sediment–water slurry, which was vigorously hand shaken for 5 min to displace gas from the sediment–water slurry into the headspace (Cadieux et al., 2016). The volume of pore water in the sediment core was calculated by drying an additional subsection of sediment. The concentration of CH_4 in the sediment cores was calculated as moles of CH_4 per unit volume of pore water in the sediment.

Littoral sediment CH_4 bubble samples were collected during open-water conditions of both 2012 and 2013 by physically disturbing the sediment in order to release entrained gas bubbles. Gas bubbles were collected using a large plastic funnel (28 cm diameter) with a gas-tight sampling tube and three-way Luer Lock valve attached to the neck (Cadieux et al., 2016). We were unable to quantify the volume of sediment samples; therefore, concentrations of CH_4 in gas collected from littoral sediments cannot be converted into pool size of CH_4 in the littoral sediments and are only an approximation of CH_4 concentration.

3.3 Concentration of CH_4

The concentrations of water column CH_4 and sediment CH_4 were measured using a Los Gatos Research (LGR) Methane Carbon Isotope Analyzer (MCIA; LGR, Mountain View, CA, USA) that was operated at KISS (Cadieux et al., 2016). All samples were processed within 24 h of collection. The total concentration of CH_4 in each sample was corrected for dilu-

tion and calculated from the sum of the measured headspace partial pressure and the dissolved CH_4 remaining after gas stripping, according to Henry's law using values from Lide and Fredrikse (1995). Instrumental uncertainty on CH_4 concentrations from the MCIA was ± 0.5 ppmv, which is 1 standard deviation of the values for gas standards analyzed during sample runs.

3.4 Inventory of dissolved CH_4

Bathymetric data were collected under open-water conditions in 2013 using a LOWRANCE HDS-5 Gen2 depthsonar built with GPS and processed by ciBioBase software by Contour Innovations LLC (Minneapolis, MN, US). The area and volume of water were derived and measured from bathymetric data. The total inventory of dissolved CH_4 in each lake was calculated by multiplying CH_4 concentrations for each depth interval by the volume of each depth interval. It was assumed that CH_4 concentrations within each depth interval were homogenous both horizontally and vertically. During open-water conditions, the depth intervals for active and storage pools were defined by redox conditions, where the storage depths are defined as intervals with $\text{DO} < 1 \text{ mg L}^{-1}$. The active depths were associated with the oxic epilimnion, where dissolved gases are susceptible to diffusive exchange with the atmosphere and exposed to atmospheric oxygen. Under ice cover, the size of the CH_4 storage pool was assumed to be that contained in the volume of water below ice.

3.5 Statistical analyses

Statistical analyses were made using IBM SPSS Statistics. Concentrations of CH_4 and chemical variables for all study lakes during each season were assessed for normal distribution via the Kolmogorov–Smirnov test, and were found to be non-normally distributed. Student's t test of unequal variance was used for testing statistically significant differences in concentrations of CH_4 between open-water and ice-covered conditions, as well as from one year to another. Systematic changes in aquatic chemistry and CH_4 concentrations were analyzed using linear regression in order to assess whether CH_4 concentrations were related to variables such as DO, temperature, DOC, and conductivity.

4 Results

4.1 Thermal structure and DO profiles

Under open-water conditions, all lakes were thermally stratified in 2012 (Fig. 4). Thermal stratification, expressed in terms of temperature difference ($\Delta T = T_{0\text{m}} - T_{z\text{max}}$), was > 12 °C in all lakes except for EVV Lower lake, where $\Delta T \approx 7$ °C. For all lakes under open-water conditions, epilimnetic temperatures were significantly warmer ($n = 30$,

Table 2. Seasonal and annual variation in median specific conductivity and DOC.

	Open water 2012*	Ice cover 2013	Open water 2013	Ice cover 2014
Specific conductivity (mS cm ⁻¹)				
EVV Upper lake	0.7 (10)	1.5 (10)	0.5 (11)	1.0 (10)
EVV Lower lake	1.2 (8)	2.9 (7)	1.0 (9)	n.d.
Teardrop lake	4.3 (10)	n.d.	1.9 (11)	3.1 (10)
Potentilla lake	0.4 (15)	0.5 (15)	0.3 (16)	0.4 (13)
South Twin lake	4.0 (10)	4.0 (9)	1.2 (9)	n.d.
DOC (mg L ⁻¹)				
EVV Upper lake	39 (4)	79 (3)	48 (4)	76 (6)
EVV Lower lake	38 (2)	80 (2)	49 (2)	n.d.
Teardrop lake	92 (3)	n.d.	58 (4)	77 (3)
Potentilla lake	11 (3)	17 (4)	11 (3)	12 (9)
South Twin lake	21 (3)	110 (2)	48 (3)	n.d.

n.d. refers to seasons when a given lake was not measured. Sample size is in parentheses.
* Open-water conditions for EVV Upper lake, Teardrop lake, and South Twin lake can also be found in Cadieux et al. (2016).

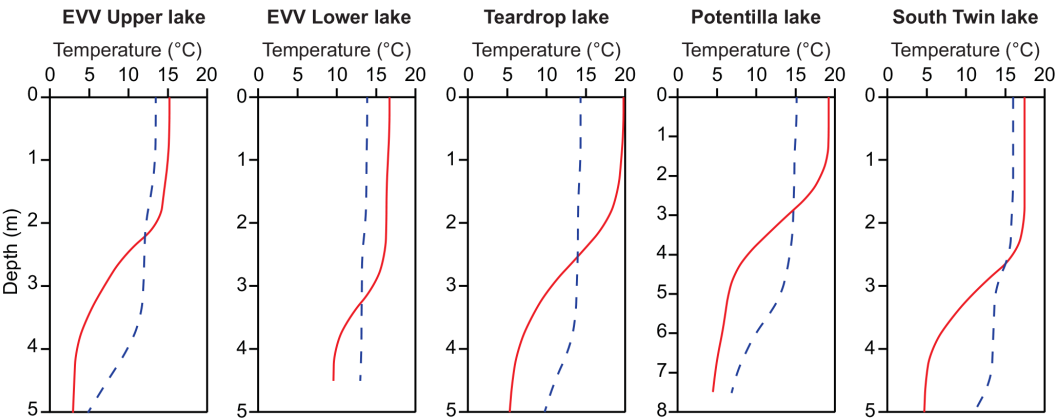


Figure 4. Profiles of temperature under open-water conditions in 2012 (red solid line) and 2013 (blue dashed line).

$p < 0.0001$) and bottom waters were cooler in 2012 than in 2013 (Fig. 4). Under open-water conditions in 2013, various levels of thermal stratification were observed, ranging from thermally stratified in EVV Upper lake and Potentilla lake ($\Delta T \approx 9^\circ\text{C}$) to isothermal in EVV Lower lake ($\Delta T \approx 1^\circ\text{C}$; Fig. 4). Under ice-covered conditions in both 2013 and 2014, lakes were nearly isothermal ($\Delta T < 2^\circ\text{C}$) except for Potentilla lake which was weakly thermally stratified under ice cover, with $\Delta T \approx 4^\circ\text{C}$ in both years.

Clinograde DO profiles were observed in all lakes under open-water conditions in 2012, wherein DO was saturated and in equilibrium with the atmosphere in the surface waters and became increasingly undersaturated down the water column (Fig. 5). Anoxia ($\text{DO} < 0.5 \text{ mg L}^{-1}$) was measured in the bottom waters of all lakes except for Teardrop lake. In EVV Upper lake, Potentilla lake, and South Twin lake, the bottom 2 to 2.5 m of the water column was anoxic. Similar

clinograde DO trends were observed under open-water conditions in 2013, although stratification was weaker (Fig. 5) and anoxia was limited to the bottom 1 m of the water column in EVV Upper lake and Potentilla lake. All lakes exhibited complete anoxia below the ice with the exception of Potentilla lake in both years. Measurable DO was observed under ice in Potentilla lake, with a clinograde profile from suboxic conditions ($7.0\text{--}5.0 \text{ mg L}^{-1}$) below the ice to 4.5 m and anoxic conditions from 5.5 m to the sediment–water interface.

4.2 Aquatic chemistry

Ionic composition varied markedly lake to lake as well as seasonally and annually (Table 2). According to a salinity classification scheme based on specific conductivity (Stewart and Kantrud, 1971), under open-water conditions in

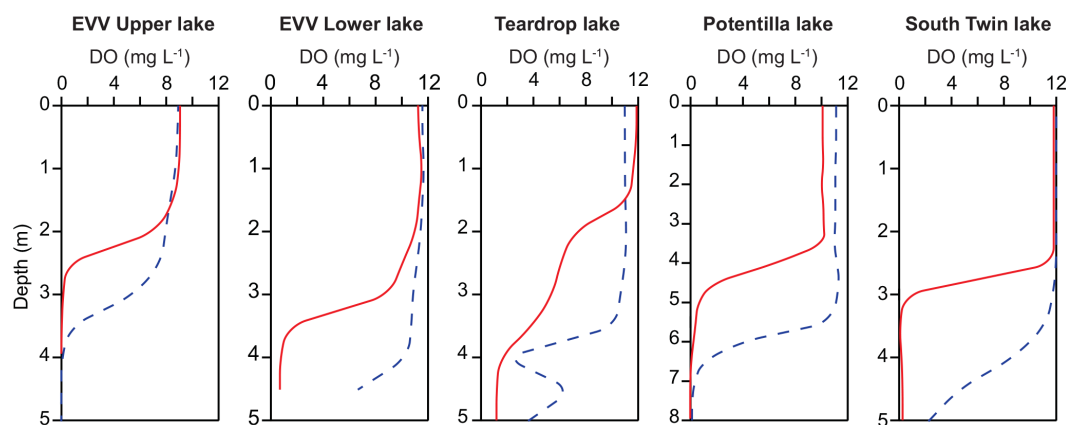


Figure 5. Profiles of DO under open-water conditions in 2012 (red solid line) and 2013 (blue dashed line).

Table 3. Concentrations of CH₄ (μM) in surface waters (0.5 m) under open-water conditions in 2012 and 2013.

	2012	2013
EVV Upper	2.7	0.9
EVV Lower	11.5	2.7
Teardrop	27.8	2.4
Potentilla	2.6	1.3
South Twin	4.3	3.5

2012, two of the study lakes were dilute ($0.04\text{--}0.5\text{ mS cm}^{-1}$; EVV Upper and Potentilla), one was slightly brackish ($0.5\text{--}2\text{ mS cm}^{-1}$; EVV Lower), and two were moderately brackish salinity, with maximum specific conductivity exceeding 2 mS cm^{-1} (Table 2). The anion abundance followed $\text{HCO}_3^- > \text{DOC}^- / \text{Cl}^- > \text{SO}_4^{2-}$ in most of lakes, regardless of conductivity. DOC^- represents the estimated charge on DOC based upon the anionic charge deficit (Driscoll and Newton, 1985; Fig. 6). EVV Upper lake was the only lake where $\text{SO}_4^{2-} > \text{Cl}^-$. Sulfate accounted for 12 % of the total anion abundance in EVV Upper lake, relative to < 3 % in the other lakes. Cation abundance in dilute lakes followed $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, whereas in slightly brackish lakes, $\text{Mg}^{2+} > \text{Na}^+ > \text{Ca}^{2+} > \text{K}^+$ was observed (Fig. 6). Overall, conductivity and ionic compositions were higher under ice-covered conditions than open-water conditions (Table 2). However, under open-water conditions in 2012, mean specific conductivity was significantly higher in all lakes than in 2013 ($n = 53$, $p < 0.0001$).

Under open-water conditions in 2012, concentrations of DOC ranged from median of 11 mg L^{-1} (Potentilla lake) to 92 mg L^{-1} (Teardrop lake; Table 2). Under ice-covered conditions, DOC was higher than open-water conditions (Table 2). No consistent trends were observed for DOC between open-water conditions in 2012 and 2013.

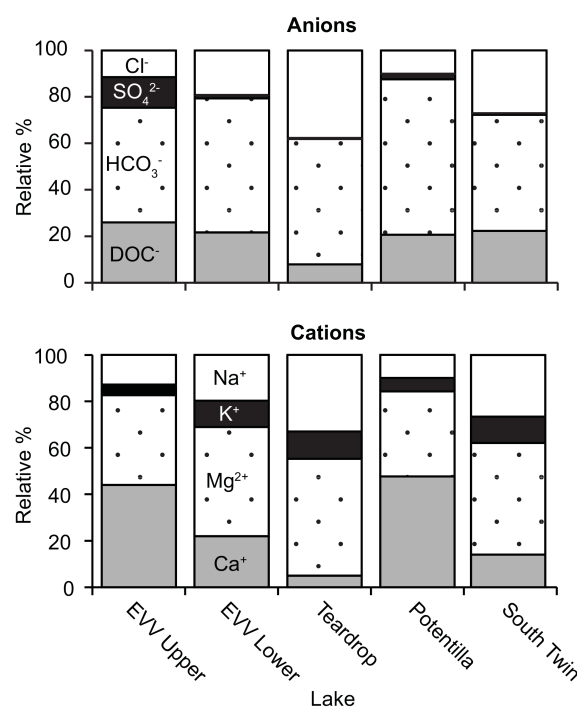


Figure 6. Relative percentages of median total charge associated with anions and cations in water samples from each of the study lakes. We assign the equivalents of missing anionic charge to DOC^- (Driscoll and Newton, 1985). In all study lakes, HCO_3^- was the dominant anion. SO_4^{2-} was the least abundant anion in all lakes except EVV Upper lake. There was no dominant cation from lake to lake.

4.3 Concentrations of CH₄

4.3.1 Dissolved water column CH₄

Concentrations of dissolved CH₄ were significantly greater under open-water conditions in 2012 than in 2013 ($n = 38$, $p = 0.008$; Fig. 6). Under open-water conditions in 2012,

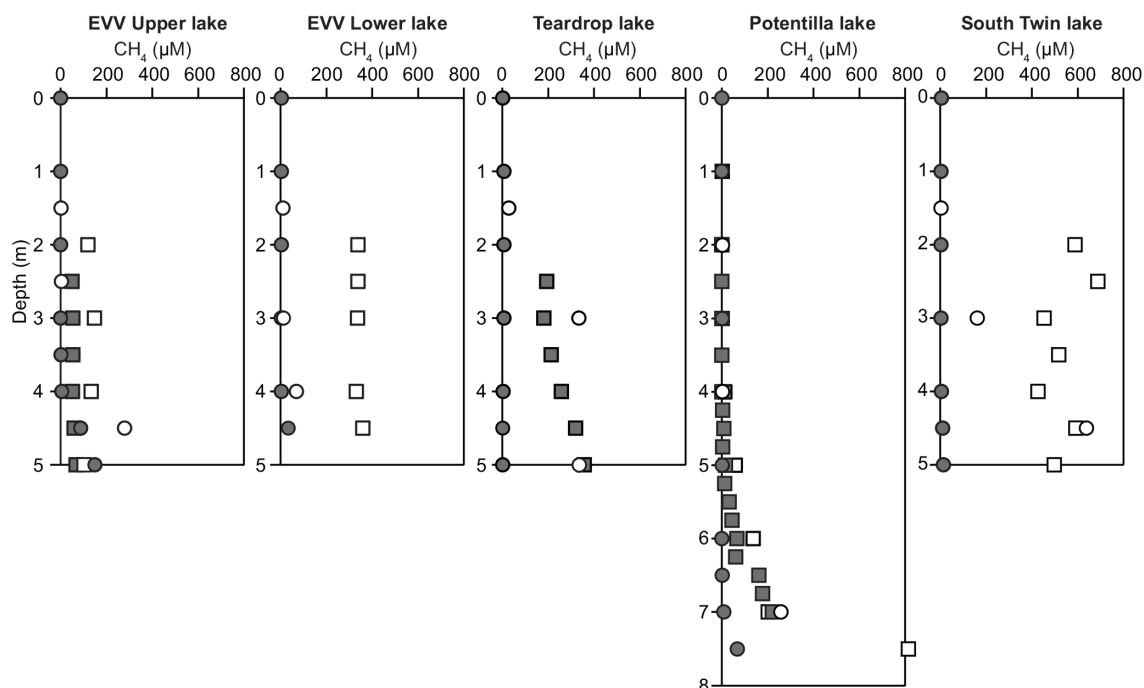


Figure 7. Profiles of dissolved CH_4 under open-water conditions (circles) in July 2012 (open) and July 2013 (closed) and ice-covered conditions (squares) in April 2013 (open) and April 2014 (closed). Concentrations of CH_4 under open-water conditions in 2013 and ice-covered conditions in 2014 can also be seen in Cadieux et al. (2016).

dissolved CH_4 concentrations in the surface waters of the study lakes ranged from 1.2 to 28 μM (Fig. 7; Table 3). In all of the lakes, CH_4 concentrations increased down the water column and were greatest in the bottom waters (Fig. 7). The highest concentration of dissolved CH_4 (640 μM) was observed at 4.5 m in South Twin lake. Similar to 2012, in 2013 CH_4 concentrations increased down the water column in all lakes except for Teardrop lake. Under open-water conditions in 2013, concentrations of CH_4 at the water–air interface ranged from 0.88 to 3.5 μM (Fig. 7). In Teardrop lake, CH_4 was <10 μM though the water column, ranging from 1.4 to 8.1 μM (Fig. 7). The highest concentration of CH_4 (150 μM) was observed at 5.0 m in EVV Upper lake.

Under ice-covered conditions, the mean concentrations of dissolved CH_4 were significantly greater than under open-water conditions ($n = 29$, $p < 0.0001$; Fig. 7). In 2013, CH_4 concentrations under ice cover were relatively uniform down the water column in EVV Upper lake (102–150 μM) and EVV Lower lake (340–360 μM) and ranged from 450 to 690 μM in South Twin lake. Only in Potentilla lake did CH_4 increase down the water column from 1.3 μM under the ice to 812 μM at the sediment–water interface (Fig. 7). The mean concentrations of dissolved CH_4 under ice cover in 2013 were significantly greater than in 2014 ($n = 29$; $p < 0.0001$; Fig. 7). In 2014, dissolved CH_4 concentrations increased down the water column from below ice cover to the sediment–water interface in all of the three lakes, from

49 to 68 μM in EVV Upper lake, 190 to 360 μM in Teardrop lake, and 0.3 to 220 μM in Potentilla lake (Fig. 7).

Linear relationships between aquatic chemistry and CH_4 concentrations were weak (Fig. 8; r^2 values for regressions ranged from 0.20 to 0.35). The highest CH_4 concentrations were correlated with both lower temperatures and lower DO; however, the lowest CH_4 concentrations did not correlate with highest temperatures or DO (Fig. 8a and b). Overall, high concentrations of CH_4 were related to high conductivity and DOC (Fig. 8c and d).

4.3.2 Whole-lake inventories and pool sizes of CH_4

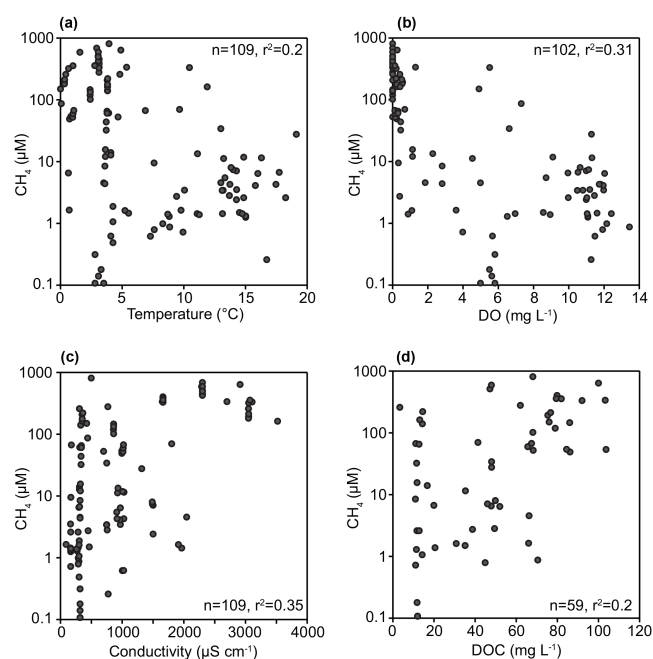
In all the lakes, the total inventory of CH_4 in the water column was higher under ice-covered conditions in 2013 and lower under open-water conditions in 2013 (Fig. 9a). Under open-water conditions, total dissolved CH_4 was 2–20 times greater in 2012 than in 2013. During all sampling dates, EVV Upper lake had the lowest CH_4 inventory among the lakes (Fig. 9a).

Under open-water conditions, the inventories of both the stored and active pools of CH_4 varied between lakes and years (Fig. 9b and c). In 2012, the majority (>50 %) of the total dissolved CH_4 inventory in the water column of EVV Upper lake and Potentilla lake was associated with the hypolimnion (Fig. 9b). EVV Lower lake was the only lake in 2012 wherein the majority of the total inventory of CH_4 occurred in the active pool of the epilimnion. In 2013, with the

Table 4. Ranges of CH₄ concentrations in profundal sediments and littoral sediment gas bubbles.

	Profundal (mM)		Littoral (ppmv)	
	Ice cover 2013	Open water 2013	Open water 2012	Open water 2013
EVV Upper lake	0.7–1.9 (6)	0.3–0.7 (5)	n.d.	473 000 (1)
EVV Lower lake	2.7 (1)	0.8–1.9 (5)	n.d.	332 000 (1)
Teardrop lake	n.d.	0.5–1.2 (5)	378 000 (1)	372 000–404 000 (2)
Potentilla lake	1.5–2.0 (4)	1.0–1.4 (5)	320 000 (1)	166 000–262 000 (2)
South Twin lake	1.4–3.4 (3)	0.4–2.2 (4)	434 000 (1)	228 000–238 000 (2)

n.d. refers to seasons when a given lake was not measured. Sample size is in parentheses.

**Figure 8.** Relationships between dissolved CH₄ concentrations from 2012 to 2014 and (a) temperature, (b) DO, (c) conductivity, and (d) DOC.

exception of EVV Upper lake, the majority of the total CH₄ inventory was in the active pool in all of the lakes (Fig. 9c). EVV Upper lake was the only lake where the majority of the total CH₄ inventory was associated with the hypolimnion (Fig. 9c). We saw no evidence of holes or moats in the ice in any of the lakes at the end of ice-covered conditions in 2013 or 2014, suggesting that the total inventories are likely relatively well conserved.

4.3.3 Sediment CH₄

In all lakes, the concentrations of CH₄ in porewaters of profundal sediments were an order of magnitude greater than dissolved CH₄ concentrations in the water column (Table 4). Under ice cover in 2013, profundal CH₄ concentra-

tions were greater than under open-water conditions in 2013 for all of the lakes. Littoral sediment CH₄ gas bubble concentrations in Potentilla and South Twin lake were greater in 2012 than 2013, whereas in Teardrop lake, concentrations of CH₄ were greater in 2013 (Table 4). Overall, the maximum littoral sediment CH₄ gas bubble concentration was 473 000 ppmv in EVV Upper lake in 2013 and the minimum was 166 000 ppmv in Potentilla 2013.

5 Discussion

5.1 Spatial variation in aquatic chemistry and methane concentrations

Aquatic chemistry of the study lakes during midsummer varied considerably among lakes with no discernable spatial trends. Chemical characteristics in each lake likely reflect interactions between basin-specific factors such as bedrock geology, basin morphometry, and macrophyte community composition. Geology in the Kangerlussuaq region has been generally described as dominated by granodioritic gneisses (Anderson et al., 2001; Jensen et al., 2002). Despite large differences in conductivity, HCO₃[−] was the dominant anion in the lakes. However, we have observed and measured sections of SO₄^{2−} minerals locally, occurring in orange-brown, thinly bedded outcrops interpreted as weathered, sulfide-rich metasediments (unpublished data). Elevated SO₄^{2−} in only EVV Upper lake leads us to suspect there is sulfide-rich, metasedimentary bedrock in the basin of this lake that has contributed to the anomalously high SO₄^{2−}. In addition, pods of marble have been described in the region previously (Taylor and Kalsbeek, 1990), although they were not identified locally. These localized marble pods could be responsible for increased Ca²⁺ in Teardrop lake. Previous work in the Kangerlussuaq regions suggests that anomalously high concentrations of DOC may be associated with abundance of littoral macrophytes (Lim and Douglas, 2003; Lim et al., 2005; Anderson and Stedmon, 2007). The lowest DOC concentrations were from Potentilla lake, which had a comparatively lower density of macrophytes in comparison to the

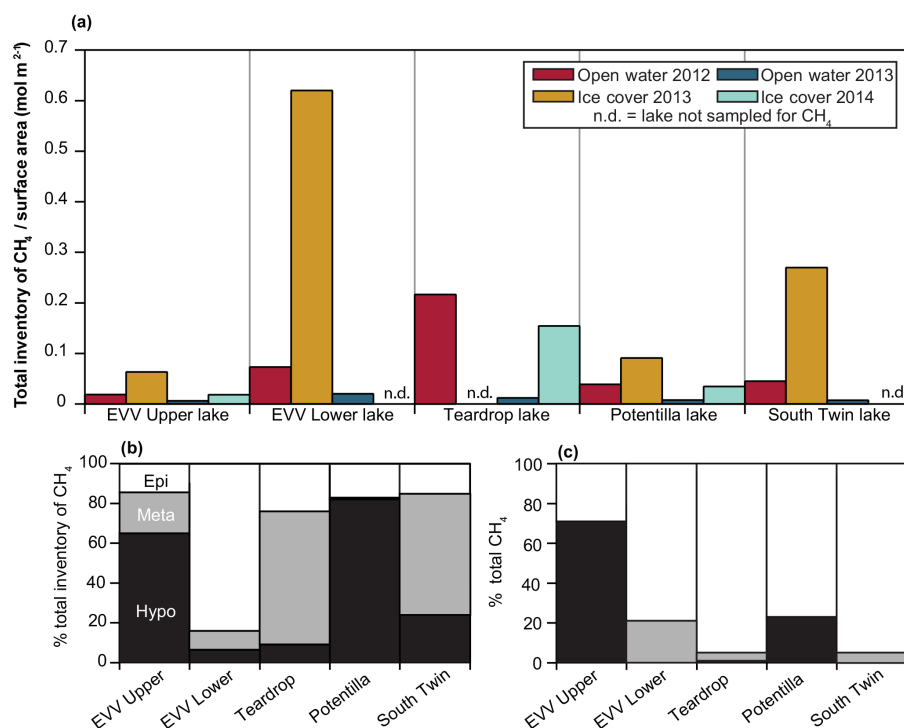


Figure 9. (a) Total inventory (moles) of CH₄ in the water column of each lake under both open-water conditions in July 2012 (black) and July 2013 (grey) and ice-covered conditions in April 2013 (white) and April 2014 (hashed lines). For seasons where the inventory was low, total moles are written above the bars; n.d. refers to seasons when a given lake was not measured. (b, c) Relative pool sizes (% of total) of dissolved CH₄ under open-water conditions in July 2012 (b) and July 2013 (c). Pools are defined by redox conditions, where the stored pool (black) is the sum of CH₄ from intervals where DO < 1 mg L⁻¹, gray represents the suboxic pool, and the active pool (white) is the sum of CH₄ from well-mixed surface intervals potentially available for direct exchange with the atmosphere.

other lakes. The relative density of macrophyte communities in these hydrologically closed basins may strongly influence DOC concentrations in the lakes.

In the water column, CH₄ concentrations are directly related to both conductivity and DOC, wherein high CH₄ concentrations correspond with both high conductivity and DOC (Fig. 8). However, we do not find a direct relationship between maximum CH₄ concentration and aquatic chemistry variables. Under open-water conditions of 2012, the maximum CH₄ concentration in the water column was from the hypolimnion of South Twin lake. While South Twin lake did exhibit relatively high conductivity, DOC concentrations were relatively low. Similarly, the highest CH₄ concentration was measured in Potentilla lake in 2013 under ice-covered conditions, corresponding to the lowest conductivity and DOC measured in the study. The lowest concentrations of CH₄ in all of the lakes were from epilimnetic waters, despite the wide range in aquatic chemistry lake to lake. In addition, EVV Upper lake had significantly higher concentrations of SO₄²⁻ than the other lakes in the study. Competition for substrates favors sulfate reduction (SR) and methanogenesis typically does not occur until SO₄²⁻ is exhausted and SR rates have decreased (Lovely and Klung, 1983, 1986;

Scholten et al., 2002; Ward and Winfrey, 1985). However, EVV Upper lake did not have the lowest concentrations of CH₄ in the water column, suggesting there were sufficient reduced carbon substrates to fuel both SR and methanogenesis. Therefore, while aquatic chemistry in the water column could be a factor influencing CH₄ production, at the level of this investigation, it alone is likely insufficient to explain the variation in CH₄ concentrations observed lake to lake, as well as seasonally and annually.

5.2 Effect of temperature on lake stratification

Ground-level air temperatures strongly influence the thermal stratification of lakes during the open-water season. Warm ground-level air temperatures during open-water conditions in 2012 (Fig. 3) resulted in epilimnetic temperatures being 1.5–5 °C higher in all of the study lakes relative to open-water conditions in 2013 (Fig. 4). Increased epilimnetic temperatures under open-water conditions in 2012 are consistent with both predictive models and measured temperatures indicating that warming climates result in higher epilimnetic temperatures (Honzo and Stefan, 1993; Fang and Stefan, 2009; Jankowski et al., 2006; Adrian et al., 2009; Coats et al., 2006). As a result of warmer epilimnetic waters, stronger

thermal stratification occurred during open-water conditions in 2012 than in 2013, with ΔT 4–9 °C higher in 2012 (Fig. 4). In addition, wind speeds were significantly lower and air pressures were higher during open-water conditions in 2012 compared with 2013 (Fig. 3), leading to reduced mixing of the water column and greater heat transfer to shallower epilimnia. Temperature and thermal structure strongly influence DO concentrations in lakes, wherein stronger thermal stratification leads to increased anoxia in the hypolimnion (Hanson et al., 2006; Adrian et al., 2009; Foley et al., 2012). For example, the extremely warm European summer of 2003 resulted in stronger thermal stratification and hypolimnetic DO depletion in Swiss lakes (Jankowski et al., 2006). Similarly, as a result of strong thermal stratification in 2012, the hypolimnia of EVV Upper lake, EVV Lower lake, Potentilla, and South Twin lake were anoxic. For comparison, 1–34 % of water column in the lakes was anoxic in 2012, whereas the percentages decreased to 0–7 % in 2013.

5.3 Effects of temperature on CH₄

Ground-level air temperature differences result in warmer surface waters and increased stratification between 2012 and 2013, but a weak linear relationship is observed between water temperatures and dissolved CH₄ concentrations (Fig. 8). Both the highest and lowest CH₄ concentrations are observed in waters < 5 °C. In freshwater environments, the concentration of dissolved CH₄ reflects the balance between CH₄ production and CH₄ consumption by anaerobic or aerobic oxidation (Duc et al., 2010; Dzyuban, 2010; Encinas Fernandez et al., 2014; Kankaala et al., 2007; Martinez-Cruz et al., 2015; Segarra et al., 2015; Smemo and Yavitt, 2011). Methane production is affected by temperature, where higher temperatures result in increased production (Duc et al., 2010). However, methanogenesis only occurs under anaerobic conditions (Borrel et al., 2011; Valentine et al., 1994; Yvon-Durocher et al., 2011). Under open-water conditions in all of the lakes, the majority of the water column is oxygenated (Fig. 5); therefore, production was likely minimal in the water column in both 2012 and 2013. Concentration of CH₄ and DO are inversely related, wherein highest concentrations occur in anoxic waters and decrease with increasing DO (Fig. 8), suggesting MOx is driving the concentration of CH₄ in the water column. However, consumption of CH₄ by microbial methane oxidation is not strongly influenced by temperature (Duc et al., 2010) and has only been demonstrated to increase with increasing temperatures under CH₄ saturated conditions (Lofton et al., 2013).

Despite the absence of a strong linear relationship between water temperature and CH₄ concentrations, warmer ground-level air temperatures correspond with increased CH₄ both in the water column and the sediments in the study lakes at the time of sampling. Under open-water conditions, CH₄ concentrations in the water column were significantly greater in 2012 than in 2013 (Fig. 8), corresponding with increased

ground-level air temperatures. Similarly, under ice-covered conditions, ground-level air temperatures were ~ 6 °C higher in 2013 than in 2014 and CH₄ concentrations in the water column were greater for the two lakes in which there are data for both years (Fig. 9). The CH₄ concentration differences occur throughout the water column, but are more pronounced in the bottom waters close to the sediment–water interface. It is possible that increased ground-level air temperatures result in increased production of CH₄ in the profundal sediments, which lead to increased concentrations in the bottom waters of each lake. However, under open-water conditions in 2012, the bottom water temperatures were colder than in 2013, suggesting profundal sediments were not warmer due to increased ground-level air temperatures. More likely, the higher CH₄ concentrations in the bottom waters during open-water conditions in 2012 were the result of increased thermal stratification and subsequent anoxia, allowing a buildup of CH₄ in the bottom waters.

The concentrations of CH₄ from profundal sediments during ice-covered conditions in 2013 were greater than from open-water conditions in 2013 (Table 4). While ground-level air temperatures were significantly colder during the 2013 ice-covered season compared to the 2013 open-water season (Fig. 3), the higher concentrations of CH₄ during ice-covered conditions may be a relic of the anomalously warm conditions from the previous open-water conditions in 2012. In the littoral sediments, where there are data for consecutive years, gas bubble CH₄ concentrations from 2012 were higher than in 2013 (Table 4), further suggesting that warmer ground-level air temperatures result in increased CH₄ production, consistent with experimental studies of methanogenesis response to higher temperature (Duc et al., 2010; Hoj et al., 2008; Lofton et al., 2013). However, it is important to note that littoral CH₄ concentrations are an estimate, as a volume of sediment/sample was unmeasured. Therefore, it is possible that the increase in littoral CH₄ concentrations is not the result of increased CH₄ production, but of a different amount of sediment disturbed.

Without temperature data for profundal and littoral sediments, it is impossible to directly determine whether warmer temperatures result in an increase in CH₄ production or whether other factors may influence production of CH₄. However, because bottom water temperatures were colder during open-water conditions in 2012 than in 2013 (Fig. 4), it is unlikely that profundal sediments were warmer in response to warmer ground-level air temperatures. In addition to temperature, methanogenesis is also influenced by the amount and quality of organic carbon substrates (Borrel et al., 2011; West et al., 2012). Lakes in this study are all embedded within continuous permafrost, with an active layer < 0.5 m thick. It is possible that the anomalously warm conditions in 2012 resulted in warming and thickening of the active permafrost layer, which could have caused organic carbon, nutrients, and ions to enter the lakes and be available for microbial utilization (Adrian et al., 2009; Kokelj et

al., 2009; Lougheed et al., 2011; Weyhenmeyer and Karlsson, 2009). However, under open-water conditions, DOC was only higher in one lake in 2012 compared to 2013 and DOC concentrations during ice-covered conditions in 2013 and 2014 were similar (Table 2). Significantly higher specific conductivity during open-water conditions in 2012 compared to 2013 was observed for all of the lakes (Table 2), which could be attributed to an additional source from permafrost thaw. Increases in DOC and conductivity were observed in thaw ponds in western Siberia during the anomalous hot summer of 2012, but these were attributed to evapoconcentration effects (Pokrovsky et al., 2013). In the Greenlandic lakes, significant water level changes between the two consecutive years of this study were not observed, so it is unlikely that the higher conductivity in 2012 was the result of evaporation.

5.4 Effects of stratification on CH₄

Enhanced thermal stratification and anoxia during open-water conditions in 2012 corresponded with significantly higher CH₄ concentrations in the water column. The most notable difference in CH₄ concentrations between 2012 and 2013 occurred within the bottom waters, which were anoxic in 2012. Under open-water conditions in 2012, the amount of CH₄ stored in the hypolimnion was 2 to 300 times higher than in 2013. The higher CH₄ concentrations may be the result of increased CH₄ production due to more extensive anaerobic conditions. However, the higher CH₄ concentrations were more likely the result of larger pools of anoxic waters in 2012 allowing for a buildup of CH₄ that corresponded in increased CH₄ storage in the water column (Fig. 8). During fall overturn, the storage pool of CH₄ is susceptible to diffusion and/or oxidation (Encinas Fernandez et al., 2014; Kankaala et al., 2007; López Bellido et al., 2009). If half of the stored CH₄ is emitted during fall overturn, as suggested by results from Fernandez et al. (2014), the fall overturn CH₄ flux would be significantly larger in 2012 than that in 2013 as a result of the more extensive anoxia in 2012.

Weaker thermal stratification during open-water conditions in 2013 meant that 93–100 % of the water column in the lakes had DO concentrations > 1 mg L⁻¹. When CH₄ diffusing from anoxic sediments reaches oxic sediment or water, the majority of it is oxidized (Bastviken et al., 2002; Dzyuban, 2010; Kankaala et al., 2007). MOx is highly efficient at consuming CH₄, thereby lowering CH₄ concentrations. The percentage of CH₄ oxidized can be estimated by assuming that CH₄ at the water–air interface originates from diffusion through the water column from the profundal sediments. Given that an increased proportion of the water column was oxic under open-water conditions 2013, we initially hypothesized that the percentage of CH₄ oxidized would be greater in 2013 than in 2012. However, under open-water conditions in 2013, the percentage of CH₄ oxidized was similar to, or less than, in 2012. Consistent with CH₄

oxidation rates from Alaskan lakes, MOx controls CH₄ concentrations when DO is present (Martinez-Cruz et al., 2015). Under warm conditions in 2012, not only were CH₄ concentrations in sediments and anoxic waters elevated but the percentage of CH₄ oxidized was also higher. Several studies suggest that MOx is important for mitigating CH₄ emissions to the atmosphere (Martinez-Cruz et al., 2015; Milucka et al., 2015; Segarra et al., 2015). However, despite the likelihood that MOx was more efficient in 2012 under warmer conditions, CH₄ concentrations in the stored pool were higher in 2012 than in 2013.

While significant variations in CH₄ concentrations and inventories were observed under between the consecutive years under open-water conditions, the amount of CH₄ stored under ice cover was significantly greater than that stored in the anoxic hypolimnion under open-water conditions (Figs. 3–6). For South Twin lake, the CH₄ storage under ice cover in 2013 was more than an order of magnitude greater than that stored in the hypolimnion during open-water conditions in 2012, and in EVV Lower lake it was two orders of magnitude greater (Figs. 3–6). In these small Greenlandic lakes, emissions during spring overturn currently reflect the largest potential flux of CH₄ to the atmosphere. Similarly, in other Arctic lakes, CH₄ emissions during spring overturn after ice breakup are usually larger than CH₄ emissions during fall overturns (Juutinen et al., 2009; López Bellido et al., 2009; Karlsson et al., 2013; Miettinen et al., 2015).

5.5 Implications for a warmer Arctic

In the Arctic, lakes are ice-covered for more than 8 months of the year (Belzile et al., 2001). The study lakes here are ice-covered ~ 10 months of the year. At sampling under ice-covered conditions, lakes have been covered ~ 8 months. In each of the study lakes, CH₄ concentrations are significantly higher under ice-covered conditions compared to open-water conditions (Fig. 7), which is also observed in other northern latitude lakes that are ice-covered the majority of the year (Juutinen et al., 2009; Martinez-Cruz et al., 2015). Ice cover impedes gas exchange between the water and the atmosphere, promoting buildup of CH₄ in the water column leading to increased CH₄ storage (Bastviken et al., 2004; Juutinen et al., 2009; Martinez-Cruz et al., 2015; Phelps et al., 1998). No holes or moats were observed in the ice cover during sampling; therefore, the total inventory of CH₄ in the water column under ice-covered conditions was stored. Similar to stored CH₄ during stratification in open-water conditions, CH₄ stored under ice is susceptible to emission to the atmosphere during spring overturns during and after ice breakup.

Projected climate change is expected to change ice cover characteristics in lakes (Fang and Stefan, 2009; Mueller et al., 2009). Ice coverage duration has already decreased for many lakes as ground-level air temperatures have increased (Bertilsson et al., 2013; Weyhenmeyer et al., 2011). As perennially ice-covered lakes begin to develop open-water

periods for at least some portions of the year, the number of seasonally frozen lakes will increase (Mueller et al., 2009). Currently, the largest efflux of CH₄ from our study lakes will most likely occur during ice breakup and spring overturn, consistent with other Arctic lakes (Karlsson et al., 2013; Miettinen et al., 2015). Changes in the duration of seasonal ice cover will result in changes in inventories of under-ice CH₄. We predict that, as the duration of ice cover decreases, the amount of CH₄ stored under ice cover will likely decrease due to the shorter time for accumulation. If the amount of stored CH₄ under ice cover decreases, this will potentially reduce the amount of CH₄ emitted during ice breakup and spring overturn.

In addition to a decrease in ice cover, our results also suggest that an increase in ground-level air temperatures will result in enhanced thermal stability and anoxia in Arctic lakes, as we observed during open-water conditions in 2012. The duration of open-water thermal stratification will also likely increase in concert with the decrease in ice cover. The combined effects of extended season and greater strength of stratification are likely to be development of higher CH₄ inventories in the water column during open-water periods. Conceptually, as anoxic zones expand in space and duration, the influence of methanogenic sediments on water column inventories of methane should increase. Currently, small lakes emit substantially more CH₄ per unit area than larger lakes during open-water conditions (Bastviken et al., 2004; Cole et al., 2007; Juutinen et al., 2009). Small, shallow lakes are more susceptible to thermal change due to increased ground-level air temperatures and will likely continue to be major CH₄ contributors to the atmosphere. In fact, our results suggest that increased warming in the Arctic will result in greater summer inventories of CH₄ and consequently larger emissions of CH₄ to the atmosphere during fall overturn in small lakes.

6 Conclusions

Over the past half century, the Arctic has warmed at a rate greater than the global average, and climate models predict further polar amplification, with the Arctic continuing to warm at a faster rate than other regions. The anomalously warm summer of 2012 in Greenland corresponded with significantly higher CH₄ concentrations under open-water conditions in a series of small lakes compared to the following year. Stronger thermal stratification under warmer conditions lead to increased CH₄ storage in the lakes. With impending warming climate, increased stratification and CH₄ storage in lakes will likely lead to greater potential fluxes during fall overturn. Currently, in these small, seasonally ice-covered Arctic lakes, the greatest concentrations of CH₄ in the water column are occurring under ice-covered conditions. Changes in seasonal ice cover will result in changes in under ice CH₄ inventories, and consequently lead to reductions in

the amount of CH₄ emitted during ice breakup and spring overturn. These results suggest that interannual variation in ground-level air temperatures may be the primary driver of changes in methane dynamics because it controls both the strength of thermal stratification and duration of ice cover. We predict that as the climate continues to warm, the greatest annual efflux of CH₄ from small Arctic lakes will shift from spring overturn to fall overturn.

7 Data availability

Data are available and can be requested by contacting the corresponding author (sbcadieux@gmail.com).

Competing interests. The authors declare that they have no conflict of interest.

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