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Methane and carbon dioxide emissions from 40 lakes along a north–south latitudinal transect in Alaska

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Abstract

Uncertainties in the magnitude and seasonality of various gas emission modes, particularly among different lake types, limit our ability to estimate methane (CH₄) and carbon dioxide (CO₂) emissions from northern lakes. Here we assessed the relationship between CH₄ and CO₂ emission modes in 40 lakes along a latitudinal transect in Alaska to physicochemical limnology and geographic characteristics, including permafrost soil type surrounding lakes. Emission modes included Direct Ebullition, Diffusion, Storage flux, and a newly identified Ice-Bubble Storage (IBS) flux. We found that all lakes were net sources of atmospheric CH₄ and CO₂, but the climate warming impact of lake CH₄ emissions was two times higher than that of CO₂. Ebullition and Diffusion were the dominant modes of CH₄ and CO₂ emissions respectively. IBS, ~ 10% of total annual CH₄ emissions, is the release to the atmosphere of seasonally ice-trapped bubbles when lake ice confining bubbles begins to melt in spring. IBS, which has not been explicitly accounted for in regional studies, increased the estimate of springtime emissions from our study lakes by 320%. Geographically, CH₄ emissions from stratified, dystrophic interior Alaska thermokarst (thaw) lakes formed in icy, organic-rich yedoma permafrost soils were 6-fold higher than from non-yedoma lakes throughout the rest of Alaska. Total CH₄ emission was correlated with concentrations of phosphate and total nitrogen in lake water, Secchi depth and lake area, with yedoma lakes having higher nutrient concentrations, shallower Secchi depth, and smaller lake areas. Our findings suggest that permafrost type plays important roles in determining CH₄ emissions from lakes by both supplying organic matter to methanogenesis directly from thawing permafrost and by enhancing nutrient availability to primary production, which can also fuel decomposition and methanogenesis.

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1 Introduction

Lakes are an important source of atmospheric greenhouse gases, methane (CH₄) and carbon dioxide (CO₂) (Battin et al., 2009; Tranvik et al., 2009; Bastviken et al., 2011). In lakes CH₄ and CO₂ have contrasting patterns of production, consumption, and exchange with the atmosphere. CH₄ is produced in anaerobic environments (mainly in sediments), while CO₂ in lakes originates from respiration throughout the water column and sediments, inflow of terrestrially derived dissolved inorganic carbon from surrounding watersheds, and photooxidation of dissolved organic carbon (DOC) (Graneli et al., 1996; Battin et al., 2009; Tranvik et al., 2009). CO₂ is also formed in lakes by aerobic oxidation of CH₄, a process that oxidizes 30–99 % of CH₄ produced in lakes (Bastviken et al., 2008; Thauer et al., 2008). Meanwhile, CO₂ is consumed by photosynthesis and other autotrophic or chemical processes that depend on pH and/or the availability of light (Madigan et al., 2009).

Despite recycling of CH₄ and CO₂ internally in lakes, a significant quantity of these greenhouse gases is released from lakes to the atmosphere (Cole et al., 2007). Most of Earth's lakes are located in northern high latitudes, overlapping the permafrost-dominated region (Downing et al., 2006; Smith et al., 2007; Grosse et al., 2013). It is estimated that CH₄ emission from lakes globally comprises about 16 % (71.6 Tg) of all human and natural atmospheric sources (Bastviken et al., 2011), and that northern lakes (> 55° N) contribute about 20 % of these emissions (13.6 Tg; Bastviken et al., 2011). Constraining CO₂ emissions is challenged by variability in patterns of CO₂ partial pressure mainly due to photosynthesis, inputs from terrestrial ecosystems, and mineralization of the organic matter (Kling et al., 1991; Battin et al., 2009; Tranvik et al., 2009). CO₂ emissions from northern lakes constitute approximately 43 % (1.2 Pg CO₂) of global emissions from lakes (Battin et al., 2009; Tranvik et al., 2009; Maberly et al., 2013). Due to a disproportionately low number of northern high latitude lakes represented in previous studies of global CH₄ emissions (Bastviken et al., 2011), and

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a paucity of studies that considered various modes of emission together, CH₄ and CO₂ emissions from northern high latitude lakes are still poorly constrained.

Geographic diversity in Alaska provides a valuable opportunity to study CH₄ and CO₂ emission patterns from lakes exhibiting wide variability in lake origin, climate, ecology, geology, and permafrost coverage. Across Arctic, Continental, and Transitional climate zones in Alaska, ecological habitats include arctic, alpine and forest tundra, and northern and southern boreal forests (Gregory-Eaves et al., 2000). The surficial geology in which Alaskan lakes are found varies primarily from fine-grain aeolian deposits; to coarser-grain coastal, glacial, fluvial and volcanic deposits; to rubble and bedrock (Karlstrom et al., 1964; Arp and Jones, 2009). Alaska is also characterized by a variety of permafrost types (Fig. 1) ranging from isolated permafrost in south-central Alaska to continuous permafrost in northern Alaska (Jorgenson et al., 2008).

Within the context of permafrost soil carbon content, Alaskan lakes can be classified depending on whether they are surrounded by yedoma-type permafrost or non-yedoma substrates (Walter Anthony et al., 2012). Yedoma is typically thick (tens of meters), organic-rich (~2% C by mass), Pleistocene-aged loess permafrost with ice content of 50–90% by volume in which deep thermokarst (thaw) lakes with high CH₄ production potentials form when ground ice melts (Zimov et al., 1997; Kanevskiy et al., 2011; Walter Anthony and Anthony, 2013). Non-yedoma permafrost can also have high organic carbon and excess ice concentrations within several meters of the ground surface; however, these organic-rich, icy permafrost horizons are typically thinner than yedoma deposits (Ping et al., 2008; Tarnocai et al., 2009). As a result, thermokarst lakes formed in non-yedoma permafrost soils are commonly shallower than yedoma lakes and may produce less CH₄ (West and Plug, 2008; Walter Anthony and Anthony, 2013; Grosse et al., 2013).

Estimating CH₄ and CO₂ emissions from northern high latitude lakes, which are seasonally covered by ice, represents a difficult task because there are at least four emission pathways, all of which have not been consistently and simultaneously measured

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in the past: (1) Direct Ebullition, (2) Diffusion, (3) Storage flux, and a newly identified (4) Ice-Bubble Storage (IBS) flux (Greene et al., 2014).

Ebullition (bubbling) has been observed as the dominant pathway of CH₄ emissions from many lakes (Casper et al., 2000; Bastviken et al., 2004; Walter et al., 2006). Since CH₄ is relatively insoluble, high concentrations in sediments lead to bubble formation and emission to the atmosphere by ebullition. In contrast, CH₄ Diffusion flux to the atmosphere is usually relatively low and occurs mainly in summer when ice cover is absent. Due to much higher solubility, CO₂ tends to occur in low concentrations in ebullition bubbles, and instead escapes lakes predominately by Diffusion (Abril et al., 2005).

During winter, ice formation on most northern lakes impedes gas emissions to the atmosphere. Dissolved CH₄ and CO₂ accumulate in the lake water column beneath the ice, resulting in gas “storage.” Storage emissions occur when dissolved CH₄ and CO₂ are emitted by diffusion when the ice melts in spring, often enhanced by full or partial lake overturn (Michmerhuizen et al., 1996; Phelps et al., 1998; Bellido et al., 2009). Storage emissions also occur in some lakes in autumn, if lake overturn caused by falling temperature brings high concentrations of dissolved gases from deeper water depths to the surface, resulting in rapid CH₄ and CO₂ emission by diffusion from the water column. Bastviken et al. (2004) coined the term “Storage flux” when they considered it in regional lake emission estimates as a function of differences in water column CH₄ stocks before and after lake ice-out, CH₄ production rates, and loss by CH₄ oxidation.

The fourth potential emission component involves CH₄ release to the atmosphere from ice-trapped ebullition bubbles in spring before the ice disappears. This mode of emissions occurs when lake ice begins to degrade and thin ice lenses that previously sealed CH₄ bubbles in and under ice during winter melt, releasing bubble gas to the atmosphere (Greene et al., 2014). Gas in small, tubular bubbles formed in lake ice by exclusion of dissolved gases as ice freezes (Gow and Langston, 1977; Langer et al., 2014) is presumably released to the atmosphere when ice degrades as well; however,

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given the substantially lower concentration of CH₄ in these non-ebullition, freeze-out bubbles (usually < 0.01 % by volume; Boereboom et al., 2012), this mode of emission is relatively insignificant in comparison to the larger ebullition-sourced bubbles, in which CH₄ concentrations typically range from 40–90 % by volume (Martens et al., 1992; Semiletov et al., 1996; Walter Anthony et al., 2010). Ponded water on the lake-ice surface can enhance the release of ice-trapped bubbles to the atmosphere and also provides the opportunity for visual observation of gas release from bubbles trapped by degrading ice (K. M. W. A. unpublished data, 2014). In this study, we investigated this emission pathway, which Greene et al. (2014) called “Ice-Bubble Storage” (IBS).

Finally, it is important to understand how changes in nutrient availability and temperature influence CO₂ and CH₄ cycling in lakes. Increasing nutrients and temperature stimulates primary production and microbial decomposition of organic matter, which in turn consumes oxygen (O₂) and enhances anaerobic decay processes, particularly in sediments, where CH₄ and CO₂ are produced (Conrad et al., 2010). The presence of O₂ facilitates aerobic CH₄ oxidation, but the efficiency of this process is controlled directly by O₂ and CH₄ concentrations and temperature (Utsumi et al., 1998; Bastviken et al., 2002; Borrel et al., 2011) and indirectly by nutrient availability (Dzyuban et al., 2010). Measurement of O₂ and CH₄ concentrations in lakes are essential for assessing global carbon cycling, and in this framework, correlating both parameters in situ has recently been promoted as an indirect means of assessing CH₄ oxidation by methanotrophs (Bastviken et al., 2004; Guerin and Abril, 2007; Sepulveda-Jauregui et al., 2012).

In this study we assessed the relationships between measured CH₄ and CO₂ emission modes in 40 lakes along a north–south Alaska transect to the lakes’ physicochemical limnology and geographic characteristics. Our goal was to assess the magnitude, variability and seasonality of individual modes of emission, particularly among the wide range of geographic lake settings in Alaska.

2 Materials and methods

2.1 Study lakes and permafrost zones

We sampled water from 40 Alaskan lakes during open-water conditions in June–July 2011 and 2012 (Fig. 1) and from 26 of the lakes toward the end of the winter ice-cover period in March–April 2011. Our study lakes were located near the road system along a north–south transect in Alaska that spans a variety of geographic and limnological settings, described previously by Gregory-Eaves (2000), Jorgenson et al. (2008), and Walter Anthony et al. (2012). Our study lakes occupied three general climatic/permafrost zones: (1) the northern study area (66–70° N, Arctic climate/continuous permafrost), (2) the interior study area (64–66° N, Continental climate/discontinuous permafrost), and the southern study area (60–64° N, transitional climate/sporadic and isolated permafrost) (Gregory-Eaves et al., 2000, Jorgenson et al., 2008). Additionally, we distinguished yedoma-type thermokarst lakes as those formed in yedoma permafrost with active, ongoing thermokarst activity from non-yedoma type lakes, which were lakes occurring in all other non-yedoma deposits in permafrost and non-permafrost soils (Fig. 1). Lake names, sizes, geographical and limnological characteristics are shown in Table 1.

2.2 Water-dissolved CH₄, CO₂ and O₂

Offshore and usually near the center of each lake, we sampled lake water at one to nine distributed depths throughout the water column for dissolved CH₄ and CO₂ concentrations and at 0.5 m depth intervals for O₂ concentrations during winter and summer. In lakes shallower than 1 m we sampled only one depth within 25 cm of the lake bottom. In the field we measured CH₄ concentration by the Headspace Equilibration-Tunable Diode Laser Spectroscopy (HE-TDLAS) method (Sepulveda-Jauregui et al., 2012) using a GasFinder 2.0 (Boreal Laser Inc., Edmonton, Canada; Appendix A). Additionally, we determined concentrations of headspace CH₄ and CO₂ in bottles of lake water in

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the laboratory following Kling (2010) using a GC-2014 gas chromatograph (Shimadzu, Addison, Illinois, USA) equipped with a flame ionization detector and a PLOT alumina column (detector temperature 250 °C, oven 40 °C, high purity Helium as carrier gas). Dissolved O₂ concentrations were measured in the field with a luminescence sensor connected to a calibrated multiparametric probe Hydrolab DataSonde (Hach LDO, Loveland, Colorado, USA).

2.3 CH₄ and CO₂ diffusion flux

We estimated the Diffusion flux of CH₄ and CO₂ (g m⁻² yr⁻¹) during summer by applying Fick's Law to our measurements of dissolved CO₂ and CH₄ in surface water following the boundary layer method of Kling et al. (1992):

$$\text{Diffusion flux} = T \cdot D \cdot z^{-1} \cdot (C_w - C_{eq}) \quad (1)$$

where T is the conversion factor from seconds to years (31 536 000); D is the molecular diffusivity of CH₄ or CO₂ (m² s⁻¹) following Kling et al. (1992); z (m) is the thickness of the surface boundary layer, assumed to be 200 μm as an average for Alaskan lakes following Kling et al. (1992); C_w is the measured gas concentration at the bottom of the boundary layer (g m⁻³); C_{eq} is the equilibrium gas concentration in surface lake water (g m⁻³) exposed to the atmosphere at the top of the boundary layer, calculated using Henry's Law constants at 22 °C of 1.47×10^{-3} and 3.61×10^{-2} mol L⁻¹ bar⁻¹ for CH₄ and CO₂, respectively (NIST, 2011).

2.4 Storage flux

To estimate Storage flux, dissolved CH₄ and CO₂ profiles were measured in spring before the ice began to melt and in summer during ice-free conditions. We multiplied the average concentration of dissolved CH₄ and CO₂ measured in samples collected from distributed depths in the water column by the height of the unfrozen water column. Storage flux (g m⁻² yr⁻¹) was calculated as the difference between total mass

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water column until the downward-growing ice encapsulates the bubbles. Since ebullition bubbles typically have a high CH₄ concentration (40–90 %) in comparison to most lake water, which is generally far below saturation with respect to CH₄ (Wilhelm et al., 1977; Sepulveda-Jauregui et al., 2012), CH₄ readily diffuses out of bubbles into the lake water column.

We collected 37 samples of ebullition bubbles trapped as pockets in lake ice from five Alaskan lakes, expanding upon the lake ice-bubble data set of Walter et al. (2008). Additionally, we opened the lake ice and placed bubble traps beneath ice, above seeps, to sample “fresh” ebullition bubbles at the lake surface before they are impeded by ice ($n = 2–41$ seeps per lake; total of 560 samples). This allowed us to compare concentrations of CH₄ in ice-trapped bubbles ($n = 2–8$ seeps per lake) to gas concentrations in “fresh” bubbles prior to ice entrapment.

Numerical modeling informed by detailed field studies of CH₄ diffusion from ice-trapped bubbles in one of our study lakes, Goldstream L. (#18) revealed that 80 % of CH₄ in bubbles trapped by ice dissolves into the lake water column in winter (Greene et al., 2014). The remaining 20 % of CH₄ ebullition trapped by ice is released to the atmosphere, either from Hotspot seep sites that open periodically throughout the winter, or from A, B, and C seep sites as ice melts in spring (i.e. IBS emissions). With input of observed ice-growth rates on a subset of lakes in each of the three study regions and mean monthly atmospheric temperatures during 2003–2013 (US National Weather Service), we employed this model to calculate a first-order estimate of IBS in 34 of the 40 study lakes in which we had measurements of both seep ebullition and water-column dissolved CH₄ concentrations, which affect the CH₄ dissolution rate from bubbles. We linearly interpolated between measured surface CH₄ concentrations in the summer and spring to estimate water-column CH₄ concentrations during the ice-cover period.

2.7 Direct ebullition in winter and summer

Since ice-bubble pockets above A, B, and C type seeps open approximately one month prior to complete disappearance of lake ice in spring (K. M. W. A., unpublished data, 2014; Greene et al., 2014), we assume in our calculations that subsequent ebullition by seeps releases fresh bubbles directly to the atmosphere through open holes during this spring melt period. Particularly high bubbling rates from “Hotspot” seeps maintain ice-free conditions above these point-sources of bubbling, allowing for Direct Ebullition to the atmosphere when air temperature is higher than -15°C (Zimov et al., 2001; Greene et al., 2014). In interior Alaska, the only region where Hotspot seeps were observed, mean monthly temperatures from 2003–2013 indicated that on average, wintertime Direct Ebullition from hotspots occurs for several weeks post-freeze up in October and in spring from February until ice melt in May. These shoulder seasons of bubble emissions through open holes in lake ice are consistent with our field observations. However, warm temperature anomalies or heavy snowfall events can also open hotspots at other times (on the scale of days) during winter (K. M. W. A. personal observation, 2014; Zimov et al., 2001; Greene et al., 2014), but these were not included in our calculations. In this study, ebullition from all seep classes during the final month of ice cover and from Hotspots during fall and spring shoulder seasons when mean monthly atmospheric temperatures were higher than -15°C (US National Weather Service) together comprised Direct Ebullition in winter.

Direct Ebullition in summer was estimated as the product of average seep densities on each lake and the sum of daily ebullition measured in bubble traps placed on representative seeps of each class in a subset of lakes during the open-water summer period (Sect. 2.5).

2.8 Seasonal and mean annual emissions

We estimated mean annual emissions from lakes as the sum of various modes of emissions seasonally: (1) Direct Ebullition from all seeps and Diffusion from the wa-

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ter column in summer (ice-free period); (2) winter (ice-cover period) Direct Ebullition emissions through ice-free Hotspot seeps during shoulder seasons and from all open seeps during the final month of the spring ice-melt season; and (3) spring emissions as the sum of first the release of IBS (ebullition seep gases trapped by lake ice) before lake ice disappears, and second, the release of lake water column Storage of dissolved gases, previously described by Michmerhuizen et al. (1996), Phelps et al. (1998), and Bastviken et al. (2004), when ice melts.

Because lakes were classified according to three geographic zones based on climate and permafrost, the average timing of ice cover was used to estimate the seasonal differences between CH₄ and CO₂ emissions for all lakes within each zone. Mean annual ice-on and ice-off dates from were compiled for years 2000–2012 for study lakes near Toolik Field Station in the northern region (1 October–18 June), our own observations of interior Alaska study lakes near Fairbanks from years 2008–2012 (8 October–9 May), and from Arp et al. (2013) and the National Park Service Inventory and Monitoring Program during years 2000–2013 for southern region lakes near Denali National Park (1 October–23 May) and southcentral Alaska, south of the Alaska Range (15 November–7 May).

2.9 Physical and chemical limnology

We measured the physicochemical limnology of lakes during winter and summer field campaigns at the same locations where dissolved gases were measured. Measurements of in situ parameters along vertical depth profiles in lakes included temperature, pH, oxidation reduction potential (ORP), and chlorophyll *a* (Chl *a*) obtained using a calibrated multiparametric probe Hydrolab DataSonde (Hach, Loveland, CO, USA). For a subset of lakes in each region, we used temperature data loggers (UA-001-08, Onset HOBO, Bourne, MA, USA) to record water temperature year-round in five-minute intervals at two depths (1 m water depth and lake bottom). Secchi disk depth (SecD) was measured with a 0.2 m Secchi disk. We collected water samples for ex situ analyses using a horizontal 2.2 L Van Dorn Bottle (WILDCO, Yulee, FL, USA). The con-

yedoma lakes ($137 \pm 129 \text{ g m}^{-2} \text{ yr}^{-1}$, $n = 32$ lakes) (Table 2); however, due to high variability among lakes, the difference was not significant. Rosie Creek beaver pond (#25), an outlier lake with particularly high CH_4 and CO_2 emissions ($317 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$; $1138 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$; Fig. 2), was formed by beaver activity in an active stream system that drains into the Tanana River. The pond was subsequently influenced by thermokarst expansion into yedoma-type deposits, which further enhances carbon cycling in the fluvial system.

The relationship between CH_4 and CO_2 emissions and other geographic parameters followed the same pattern to the extent that they were related to characteristics of yedoma and non-yedoma permafrost soils (Table 3). For instance, yedoma is characterized by eolian deposits, which among the surface geologic deposit types was also most strongly related to CH_4 and CO_2 emissions. Among our study lakes, yedoma lakes occurred in the interior Alaska region (Fig. 1) and tended to have a dystrophic state, parameters that were both related to CH_4 and CO_2 emissions. Since the particular yedoma lakes in our study were relatively small lakes ($\leq 0.1 \text{ km}^2$), lake area was a morphologic parameter closely related to CH_4 and CO_2 emissions.

Regressions models showed that physical and chemical limnological parameters (Table 1) explained 19–63 % of deviation in the different flux pathways of CH_4 emissions (Table 4). Total CH_4 emission was correlated with Area, SecD, PO_4^{3-} , and TN (Table 4). We did not find any relationships between total CO_2 and the lakes' physicochemical characteristics, probably due to chemical equilibrium in water.

3.2 Modes of CH_4 and CO_2 emission

Total annual ebullition, consisting of Direct Ebullition in summer and winter as well as springtime release from IBS, was the dominant mode of CH_4 emission in lakes, comprising 86 % of total annual emissions from yedoma lakes and 65 % from non-yedoma lakes (Table 2). Summer Direct Ebullition was higher in yedoma-type lakes ($25.9 \pm 16.1 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, $n = 6$ lakes, excluding lake # 25) than non-yedoma lakes

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3.3 Seasonal emissions

Figure 4 illustrates the contribution of different gas emissions pathways to annual emissions by season. Approximately three quarters of annual CH₄ emissions were released from lakes during the open water summer season: 71 % and 79 % of total annual CH₄ emissions in yedoma lakes and non-yedoma lakes respectively were the sum of summer Direct Ebullition and Diffusion. Spring and winter CH₄ emissions were also important. From yedoma lakes, first 13 % of total annual emissions occurred via IBS in spring when the ice started to degrade; subsequently, water column Storage release of dissolved gases was 3 % of total annual emissions. From non-yedoma lakes, total springtime emissions were 14 % of annual, consisting first of IBS (9 %) followed by Storage (5 %). Wintertime emissions via Direct Ebullition from ice-free holes above seeps were 13 % of total annual emissions from yedoma lakes and 7 % from non-yedoma lakes. It is of interest to note that accounting for IBS, a newly recognized mode of emission, increased the estimate of springtime CH₄ emissions based on the more commonly reported Storage emission by 320 %.

Seasonally, ~ 100 % and 92 % of total annual CO₂ emissions from yedoma and non-yedoma lakes respectively occurred in summer by Diffusion from the open water surface. The remaining 8 % of annual emissions in non-yedoma lakes occurred in spring from water column Storage flux (7 %) and winter Direct Ebullition (less than 1 %) (Table 2 and Fig. 2).

3.4 Physical and chemical patterns

The difference between yedoma and non-yedoma lakes was observed in several physical and chemical parameters (Tables 1, 3, and 5). Southern lakes (non-yedoma lakes) are deeper and larger than Interior lakes (mostly yedoma lakes), while northern lakes (non-yedoma lakes) were not statistically different in morphology from lakes in the other regions.

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Deep lakes (> 20 m), moderately deep lakes (usually > 6 m) with adequate wind protection, and all yedoma lakes, owing to their small surface area to volume ratios and high TOC concentrations were thermally stratified in summer. Exceptions were two yedoma-type lakes with creeks flowing through them (Killarney L. #20 and Rosie Creek beaver pond #25) and a small, shallow, yedoma thermokarst pond (Stevens Pond #22, 1.1 m) that were semi-stratified. In contrast, shallow, non-yedoma lakes (usually < 3 m) and non-yedoma lakes located in mountain regions with large surface area to volume ratios and high wind conditions were well mixed.

In winter, most lakes demonstrated inverse stratification. The coldest temperatures were at the surface of the water column beneath ice and water temperature tended to increase with depth. We found that winter bottom temperature was significantly different between northern lakes ($1.3 \pm 1.5^\circ\text{C}$) and southern lakes ($2.6 \pm 1.1^\circ\text{C}$), but none of these were significantly different from lake bottom temperature in Interior Alaska ($1.4 \pm 1.0^\circ\text{C}$), which is mainly due to the contrasting climatic conditions and the relatively shallow depths of northern lakes compared to southern lakes.

In most lakes, if there was a dissolved O₂ (DO) gradient, then DO was highest near the lake surface and decreased with depth in winter and summer. Three exceptions were El Fuego L. (#11), 91 L. (#27) and Dolly Varden L. (#36), where we observed an increase in DO with depth in summer, likely due to benthic photosynthesis. Among yedoma lakes, lake-bottom dissolved oxygen (DO) concentrations were < 0.1 mg L⁻¹ in both winter and summer. In contrast, 81 % of the 32 non-yedoma lakes had well-aerated lake bottoms in summer; the lake-bottom water DO concentration in the other 19 % of lakes was < 0.1 mg L⁻¹. In winter, we observed the reverse pattern among non-yedoma lakes: 76 % of 17 non-yedoma lakes measured had lake-bottom DO < 0.1 mg L⁻¹ while 24 % of non-yedoma lakes, all which were southern lakes, had well-aerated lake bottoms in winter. All temperature and DO profiles measured on the study lakes are shown in Supplement Fig. B.

DO concentrations were inversely related to dissolved CH₄ concentrations in the lake bottom water during winter and summer (Fig. 5). This relationship suggests a strong

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lition". Background Ebullition is thought to originate primarily from methanogenesis in surface lake sediments in summer; in contrast, ebullition seeps consist of bubble tubes that allow CH₄ produced at depth in sediments to migrate efficiently as bubbles to the sediment surface in summer and winter by the repeated release from point-source locations. Bubble traps placed in seep and non-seep locations and monitored year-round in two Siberian lakes showed that seep ebullition dominated total annual CH₄ emissions. Background Ebullition was high in summer, nearly absent in winter, and altogether comprised ~25% of total annual CH₄ emissions in the Siberian lakes. Preliminary results from bubble-traps placed in some of our Alaskan study lakes in locations where no seep ebullition bubbles were observed in winter also showed high summertime bubbling (K. M. W. A. unpublished data, 2014). This suggests that Background Ebullition occurs in Alaska too. Since our estimate of lake ebullition in the Alaskan lakes is based solely on discrete seeps and does not include non-seep Background Ebullition, we consider that our estimate of total lake ebullition is below the total actual ebullition flux. Given that methanogenesis is highly temperature dependent (Dunfield et al., 1993; Schulz et al., 1997; Nguyen et al., 2010; Marotta et al., 2014; Yvon-Durocher et al., 2014) and surface lake sediments heat up in summer, accounting for Background Ebullition would likely increase the total ebullition emissions from all of the Alaskan study lakes.

The Ice-Bubble Storage (IBS) mode of emission described here is a newly recognized CH₄ flux component in lakes (Greene et al., 2014) that has not previously been included in regional studies. Given the coarse temporal resolution of temperature and dissolved gas data used as input to the IBS model, we acknowledge that our estimate of IBS is a first-order approximation. However, strong agreement in the relative importance of IBS in the annual CH₄ budget of Goldstream Lake (#18) in this study using coarse resolution data (IBS 6% of total annual CH₄ emission) vs. the estimate from Greene et al. (2014) using highly detailed field data allowing detailed modeling (IBS was 5% and 9% of total annual emissions in two different years), suggests that our first-order approximations of IBS may be valid. Since IBS was an important mode of CH₄ emissions among our study lakes (13% and 9% of total annual emissions

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in yedoma and non-yedoma lakes, respectively), it is likely that past estimates of the magnitude and seasonality of CH₄ emissions from lakes with ebullition seeps were incomplete. Greene et al. (2014) found that a large fraction (~80%) of CH₄ diffused from ebullition bubbles trapped under lake ice into the lake water in Goldstream L. Coarser-resolution modeling of the IBS process for our study lakes also suggested that approximately 80% of CH₄ dissolved out of ice-trapped bubbles. Detailed measurements and modeling in Goldstream L. showed that about half of this re-dissolved CH₄ was ultimately oxidized (Greene et al., 2014). Due to a paucity of field data, we did not model CH₄ oxidation; however, given the observed CH₄ oxidation potentials in our study lakes through incubation studies (Martinez-Cruz et al., 2014), it is likely that some fraction of the re-dissolved ebullition bubbles is oxidized. The un-oxidized fraction of dissolved CH₄ is subject to release to the atmosphere via water column convection and diffusion as Storage emissions in spring when ice more completely disintegrates and as Diffusion during summer (Greene et al., 2014). Thus the Storage and Diffusion modes of emission may involve not only dissolved CH₄ that diffused out of lake sediments, but also dissolved CH₄ that first originated as ebullition bubbles prior to ice entrapment. Since ebullition seeps were important components of whole-lake CH₄ emissions in all of our study lakes, as well as in tens of other lakes previously reported in Alaska (Walter Anthony et al., 2012) and Siberia (Walter et al., 2006; Walter Anthony et al., 2010), IBS should be studied and accounted for in global lake CH₄ emission budgets.

Lake CH₄ Storage emission estimates for our Alaska study lakes ($0.5 \pm 0.7 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$; Table 2), which comprised ~4% of total annual emissions, were highly variable and on the same order of magnitude as the mean estimate for other northern lakes reported by Bastviken et al. (2004) ($2.4 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$) and Bastviken et al. (2011) ($0.8 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$; pan-Arctic). Storage emission from global lakes ranged from <0.1 to $37 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, comprising 0.5% to 81% of the total annual emissions (Bastviken et al., 2011). This also suggests high variability in this emission mode among global lakes. The large relative error for Storage flux measured

among our Alaska study lakes (140%; mean \pm SD, $0.5 \pm 0.7 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$) confirms that there is large variability associated with this mode of emission; however, CH_4 Storage emissions in our Alaska study lakes were $< 2.7 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, except in Rosie Creek beaver pond (#25, $39 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$). In other northern lakes, full or partial mixing of the water column leads to the release of stored gas during a 10–15 day period associated with ice-out (Phelps et al., 1998; Striegl and Michmerhuizen, 1998; Bellido et al., 2009). Additionally, full or partial turnover of the lake water column in fall can release additional stored CH_4 (Bastviken et al., 2004; Bellido et al., 2009). Since we estimated only spring Storage emission and did not take into account potential additional emissions associated with fall turnover, our Storage values are likely an underestimate.

4.2 Geographic patterns of lake CH_4 and CO_2 emissions in Alaska

Previous regional analyses of northern lake emissions found a relationship between CH_4 emissions from lakes and latitude that was explained by temperature (Marotta et al., 2014; Yvon-Durocher et al., 2014). Primary production in warmer climates supplies more organic substrate for methanogenesis, and methanogenesis is sensitive to temperature. However, the lakes in these studies were not permafrost-affected. In our N-S Alaska transect we did not find a relationship between lake CH_4 emissions and latitude or temperature. We attribute this finding to the presence and geographic diversity of permafrost types (yedoma vs. non-yedoma) (Jorgenson et al., 2008; Kanevskiy et al., 2011), which is more a function of periglacial history and topography in Alaska than it is of latitude or recent climate. While methanogenesis in surface sediments of lakes globally is fueled by contemporary autochthonous primary production and allochthonous organic matter supply (processes typically controlled by latitude and climate in undisturbed systems), thermokarst-influenced lakes have an additional, deeper source of organic matter that fuels methanogenesis: thawing permafrost in the thaw bulbs beneath lakes and along thermally eroding shorelines. Organic matter supplied by thawing per-

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mafrost, particularly in lakes formed in thick, organic-rich yedoma-type deposits, can overwhelm the more contemporary organic carbon substrates supplied to surface lake sediments (Kessler et al., 2012).

The interior Alaska yedoma lakes, which had the highest CH₄ and CO₂ emissions, are largely thermokarst lakes formed by thaw of organic-rich yedoma permafrost. Radiocarbon ages (18–33 kyr BP) and δD-depleted values of CH₄ in ebullition bubbles collected from the interior Alaskan thermokarst lakes suggested that thaw of late Pleistocene yedoma organic matter fuels methanogenesis in these lakes (Walter et al., 2008; Brosius et al., 2012). The 6-fold difference in CH₄ emissions between yedoma lakes and non-yedoma lakes throughout the rest of Alaska is likely explained by the variability in the availability of recently thawed permafrost organic matter, which provides a larger additional substrate for methanogenesis in the yedoma lakes owing to the thickness (usually tens of meters) of organic-rich yedoma deposits (Kanevskiy et al., 2011; Walter Anthony et al., 2012).

Previous research using stable isotopes and radiocarbon dating of CH₄ in ebullition bubbles in yedoma lakes demonstrated that stronger ebullition seeps originate from greater depths beneath the sediment-interface and are characterized by older ¹⁴C ages and more depleted δD values associated with thaw of Pleistocene-aged yedoma permafrost (Walter et al., 2008). The disproportionately large contribution of strong Hotspot ebullition seeps to emissions from yedoma lakes (mean ± SD: 17 ± 12 % of total annual emissions) in this study suggests microbial production of CH₄ at greater depths in sediments beneath yedoma lakes. In contrast, the absence of Hotspot ebullition seeps in non-yedoma lakes, which we observed to also have dense sediments, suggests that CH₄ formation by microbial decomposition of organic matter is more restricted to shallower sediment depths in the non-yedoma lakes.

The relationship between ebullition, dissolved CH₄ concentration and lake type (Fig. 6) also indicates that ebullition seeps releasing CH₄ produced deep in the thaw bulb enhance CH₄ cycling in yedoma lakes more than in non-yedoma lakes. Yedoma lakes, which had a higher density of ebullition seeps than non-yedoma lakes (Sect. 3.2),

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had both higher volumes of CH₄-rich bubbles impeded by lake ice and higher concentrations of dissolved CH₄ in the lake water in winter (Fig. 6a, $\rho = 0.72$). Based on Greene et al. (2014), in which 87 % of dissolved CH₄ in the water column in winter originated from CH₄ dissolution from ebullition bubbles trapped by lake ice, we attribute the higher concentrations of dissolved CH₄ in the yedoma study lakes to the process of CH₄ dissolution from ice-trapped bubbles. Modeling results, which showed that approximately 80 % of CH₄ in bubbles trapped by lake ice in our study lakes dissolved into the water column, support this conclusion. Other important processes that would also control dissolved CH₄ concentrations in lake water are diffusion from sediments and CH₄ oxidation. Given the thicker CH₄-producing sediment package beneath yedoma lakes, we would expect diffusion of dissolved CH₄ from yedoma lakes to be higher than that of non-yedoma lakes. Ex situ incubations by Martinez-Cruz et al. (2014) on a subset of our Alaska study lakes also showed that yedoma lakes had higher CH₄ oxidation potentials, owing in large part to higher concentrations of the dissolved CH₄ substrate in these lakes. Compared to winter, the weaker correlation between dissolved CH₄ and Direct Ebullition in summer (Fig. 6b, $\rho = 0.42$) has several potential explanations. First, in summer, ebullition bubbles escape directly to the atmosphere, so the dissolved CH₄ stock of the water column is not supplied from ice-trapped bubble dissolution like it is in winter unless residual winter-dissolved bubble CH₄ remains in the water column in summer. Second, dissolved CH₄ diffusing from lake sediments in summer may be more immediately oxidized by aerobic CH₄ consumption since O₂ is more available in lake water from atmospheric diffusion and autochthonous primary production. Finally, higher PO₄³⁻, TN and Chl *a* concentrations in yedoma lakes (Table 1) suggests primary production in yedoma lakes may contribute relatively more substrate to methanogenesis in surface sediments. CH₄ produced in surface sediments more readily escapes to the water column via diffusion than CH₄ produced in thaw bulbs, which preferentially escapes by ebullition (Tan et al., 2014). Higher diffusion from surface sediments would support higher concentrations of dissolved CH₄ in lake water, a process that can be independent of ebullition from thaw bulbs in summer. This explanation is supported by

two times higher summer Diffusion emissions from yedoma lakes compared to non-yedoma lakes (Table 2), despite higher observed CH₄ oxidation potentials in yedoma lakes vs. non-yedoma lakes (Martinez-Cruz et al., 2014).

CO₂ Diffusion, which was ~ 100 % and 92 % of total annual CO₂ emissions from yedoma and non-yedoma lakes respectively, was 6 times higher on average in yedoma lakes than in non-yedoma lakes. Potential explanations include enhanced CO₂ production associated with yedoma organic matter decomposition, photooxidation of the large DOC pool observed in the dystrophic yedoma lakes, and potentially higher rates of CH₄ oxidation in yedoma lakes (Martinez-Cruz et al., 2014) generating more CO₂ in the lake water columns. Possible differences in watershed sizes draining into lakes could also influence CO₂ concentrations in lakes and Diffusion emissions since terrestrial dissolved inorganic carbon often dominates lake CO₂ pools (Kling et al., 1992; Battin et al., 2009; Tranvik et al., 2009). Since we did not study these processes, and since our calculations contain uncertainty associated with the assumption that single-day measurements of dissolved CO₂ and CH₄ in lakes represent the mean flux for the entire open water period, further research is needed to validate these hypotheses in the Alaskan lakes.

4.3 Dissolved CH₄ and O₂ dynamics

Dissolved O₂ concentration is a useful parameter for predicting the CH₄ concentrations in Alaskan lakes. The inverse relationship between CH₄ and O₂ concentration in lake water (Fig. 5) suggests that low dissolved O₂ levels in lakes are due to high microbial activity, which in turn leads to optimal anoxic conditions for methanogenesis (Boon and Mitchell, 1995).

There are several possible explanations for the pattern of seasonally higher dissolved CH₄ and lower O₂ concentrations in winter among lakes (Fig. 5): (1) Ice cover inhibits O₂ transfer from the atmosphere into the water column (White et al., 2008); (2) Primary production in lakes declines as day length shortens (White et al., 2008; Clilverd et al., 2009); (3) Snow cover impedes light transfer, further extinguishing photosynthe-

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lakes compared to non-yedoma lakes is consistent with the geographic patterns previously observed in Siberian lakes. Higher aquatic production observed in Siberian yedoma lakes compared to non-yedoma lakes in the same climate zone was attributed to fertilization of the yedoma lakes by nitrogen- and phosphorus-rich thawing yedoma permafrost (Walter Anthony et al., 2014).

The negative correlation between CH₄ emissions and lake area indicates that small lakes had higher total annual CH₄ emissions. This finding is driven by yedoma lakes, which were on average much smaller than non-yedoma lakes (Table 1). It is also consistent with lake CH₄ emission patterns in other regions whereby smaller lakes have higher CH₄ emissions due to a stronger relative contribution of littoral organic matter to whole-lake methanogenesis (Bastviken et al., 2004).

Significant differences between other limnological and geographical parameters also distinguished yedoma from non-yedoma lakes. Dystrophy (i.e. brown-water lakes due to high DOC concentrations; Wetzel, 2001), characterized yedoma lakes. Due to the absorption of incoming solar radiation by DOC in the surface water (indicated by TOC, which corresponds approximately to DOC in natural lake ecosystems (Tranvik et al., 2009, Table 1), the yedoma lakes were thermally stratified in summer, and had relatively cold, anoxic hypolimnia nearly all year round. Since non-yedoma lakes have a variety of different origins, lake depth was highly variable among them; however, lower concentrations of DOC in non-yedoma lakes and, in many cases, large surface area to volume ratios that facilitated water column mixing by wind contributed to less intense stratification or the absence of stratification among many of the non-yedoma lakes.

4.5 Climate warming impacts of Alaskan lake emissions

Previously, Kling et al. (1992) showed that tundra lakes near Toolik Field station emit CH₄ and CO₂ via Diffusion. More recently, Walter Anthony et al. (2012) recognized the importance of CH₄ ebullition from ecological seeps in Alaskan lakes (0.75 Tg CH₄ yr⁻¹); however, this represented the quantity of ebullition seep CH₄ released from sedi-

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ments rather than the magnitude of atmospheric emissions. Since ebullition emission is partially impeded by lake ice in winter, and a fraction of CH₄ dissolved out of bubbles beneath ice is oxidized by microbes (Greene et al., 2014), ebullition emissions to the atmosphere are lower than what is released annually from sediments.

5 This study is the first to consider multiple modes of emissions for CO₂ and CH₄ together, including the ice-bubble storage process, for a large number of Alaskan lakes spanning large geographic gradients. Scaling total annual CH₄ and CO₂ emissions observed among yedoma and non-yedoma lakes to the extent of these lake types in Alaska (Walter Anthony et al., 2012) ($44 \pm 17 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1} \times \sim 8800 \text{ km}^2$ yedoma lakes; $8 \pm 4 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1} \times \sim 41\,700 \text{ km}^2$, non-yedoma lakes), we estimate that yedoma and non-yedoma lakes emit a total of 0.72 Tg CH₄ yr⁻¹ ($\sim 0.39 \text{ Tg CH}_4 \text{ yr}^{-1}$ from yedoma lakes, 0.33 Tg CH₄ yr⁻¹ from non-yedoma lakes). This estimate of Alaska lake emissions increases the previous estimate of Alaska's wetland ecosystem emissions (3 Tg CH₄ yr⁻¹, Zhuang et al., 2007), in which lakes were not included, by 24%.

10 Our estimate of lake CH₄ emission is conservative because it does not include Background (non-seep) Ebullition or Storage emissions associated with fall lake turnover events.

If we assume that our study lakes represent the CH₄ and CO₂ emission dynamics of all lakes in Alaska and account for the 34-fold stronger global warming potential of CH₄ vs. CO₂ over 100 years (GWP₁₀₀; Myhre et al., 2013), the impact to the climate based on CO₂ equivalent (CO₂-eq) emissions from yedoma lakes is $\sim 20 \text{ Tg CO}_2\text{-eq yr}^{-1}$ ($13 \text{ Tg CO}_2\text{-eq yr}^{-1}$ from CH₄ and $7 \text{ Tg CO}_2 \text{ yr}^{-1}$ from CO₂). For non-yedoma lakes, the total climate impact is $\sim 17 \text{ Tg CO}_2\text{-eq yr}^{-1}$ ($11 \text{ Tg CO}_2\text{-eq yr}^{-1}$ from CH₄ and $6 \text{ Tg CO}_2 \text{ yr}^{-1}$ from CO₂). These results have several important implications. First,

20 CH₄ emissions have nearly twice the impact on climate as CO₂ emissions among all Alaskan lakes. Second, the climate impact of yedoma and non-yedoma lakes in Alaska due to carbon greenhouse gas emissions are approximately equal, despite yedoma lakes comprising less than 1/5 of the total lake area in Alaska. The disproportionately large climate impact of CH₄ emissions from yedoma lakes is due in large part to thaw of

deep, organic-rich yedoma permafrost beneath these lakes; however, higher concentrations of nitrogen, phosphorus and chlorophyll *a* in these lakes suggests enhanced primary production in the lakes, which can also fuel decomposition and methanogenesis, as recently demonstrated in Siberia (Walter Anthony et al., 2014).

5 Conclusions

We have shown that Alaskan lakes are net sources of atmospheric CH₄ and CO₂. Total annual CH₄ and CO₂ emissions were dominated by ebullition and diffusion, respectively; however, the climate warming impact of CH₄ emissions was twice that of CO₂. Our 40 study lakes spanned large gradients of physicochemical limnology and geography in Alaska. We attribute the 6-fold higher CH₄ and CO₂ emissions observed in thermokarst lakes formed in icy, organic-rich yedoma permafrost in interior Alaska compared to non-yedoma lakes throughout the rest of Alaska to enhanced organic matter supplied from thawing yedoma permafrost, which is typically thicker than the organic-rich strata of non-yedoma soils. Higher total nitrogen, PO₄³⁻, and Chl *a* concentrations in yedoma lakes suggest that higher primary production may also enhance organic substrate supply to decomposition and greenhouse gas production in these lakes. Consideration of multiple modes and seasonality of CH₄ and CO₂ emissions revealed that summer emissions were largest. However, winter and spring emissions of CH₄, including Direct Ebullition through holes in lake ice and the ice-bubble storage and release process, were also significant components of the annual CH₄ budget. Our results imply that regional assessments of lake CH₄ and CO₂ emissions in other parts of the pan-Arctic should take into account the myriad of emission modes, lake type and geographic characteristics, such as permafrost type.

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Appendix A: Methods

A1 Dissolved gas measurements

We used the Headspace Equilibration-Tunable Diode Laser Spectroscopy (HE-TDLAS) technique, described in detail by Sepulveda-Jauregui et al. (2012), to measure the concentration of CH₄ dissolved in lake water. Briefly, we collected water samples using a Van Dorn Bottle (WILDSCO, Yulee, FL, USA) and gently transferred 60 mL into three borosilicate vials (100 mL volume) using disposable polypropylene syringes for triplicate measurements. Vials were immediately sealed with butyl rubber stoppers and aluminum crimp caps. The vials containing the water samples were shaken vigorously for 10 s to transfer CH₄ from the water into the vials' headspace for subsequent measurement with the GasFinder 2.0.

In addition to HE-TDLAS, we also measured dissolved CH₄ and CO₂ in a subset of samples using the traditional headspace equilibration method by gas chromatography (Kling et al., 1992). Water samples (10 mL) collected with the Van Dorn Bottle were transferred into 25 mL glass serum bottles and immediately sealed with butyl rubber stoppers and aluminum crimp caps. Serum bottles were stored upside down and frozen until laboratory analysis. In the laboratory, we thawed the samples to room temperature, shook bottles for 10 s to equilibrate headspace and water samples, and then measured CH₄ and CO₂ of the headspace by gas chromatography (Shimadzu GC-2014).

A2 Seep ebullition

GPS-mapped ebullition seeps were classified as A, B, C and Hotspot types, based on ice-bubble morphologies. This classification system has been described in detail, with example photographs and bubble morphology classification criteria presented in multiple previous publications (Walter et al., 2006, 2008; Walter Anthony et al., 2010, 2013). Briefly, A-type ebullition seeps are relatively small clusters of ebullition bubbles in which individual bubbles stack on top of each other in the winter ice sheet without

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long transects per lake (median 4 transects per lake), divided by the total area surveyed. In a recent comparison of methods for quantifying ebullition, Walter Anthony and Anthony (2013) showed that when at least three 50 m transects per lake are used to quantify seep ebullition, the estimate of mean whole-lake ebullition is 4–5 times more accurate than the mean flux determined by placement of seventeen 0.2 m² bubble traps randomly distributed across lake surfaces.

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Author contribution. K. M. Walter Anthony and A. Sepulveda-Jauregui conceived of the study. A. Sepulveda-Jauregui and K. M. Walter Anthony wrote the manuscript. K. M. Walter Anthony, A. Sepulveda-Jauregui, K. Martinez Cruz and F. Thalasso were responsible for field and lab work. A. Sepulveda-Jauregui conducted statistical analyses. S. Greene modeled ice-bubble storage emissions. All authors commented on the composition of the manuscript.

References

Abril, G., Guerin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A., Varfalvy, L., Dos Santos, M. A., and Matvienko, B.: Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), *Global Biogeochem. Cy.*, 19, G02024, doi:10.1029/2007JG000608, 2005.

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Arp, C. D. and Benjamin, M.: Geography of Alaska lake districts: Identification, description, and analysis of lake-rich regions of a diverse and dynamic state, in: US Geological Survey Scientific Investigations Report, U.S.G.S.S.I., USA, 2009.

Arp, C. D., Jones, B. M., and Grosse, G.: Recent lake ice-out phenology within and among lake districts of Alaska, USA, *Limnol. Oceanogr.*, 58, 2013–2028, 2013.

Bastviken, D. and Tranvik, L.: Measurement of methane oxidation in lakes: a comparison of methods, *Environ. Sci. Technol.*, 36, 3354–3361, 2002.

Bastviken, D., Cole, J., Pace, M., and Tranvik, L.: Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate, *Global Biogeochem. Cy.*, 18, GB4009, doi:10.1029/2004GB002238, 2004.

Bastviken, D., Cole, J. J., Pace, M. L., and Van de Bogert, M. C.: Fates of methane from different lake habitats: Connecting whole-lake budgets and CH₄ emissions, *J. Geophys. Res.-Biogeo.*, 113, G02024, doi:10.1029/2007JG000608, 2008.

Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M., and Enrich-Prast, A.: Freshwater methane emissions offset the continental carbon sink, *Science*, 331, 50, 2011.

Battin, T. J., Luysaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., and Tranvik, L. J.: The boundless carbon cycle, *Nat. Geosci.*, 2, 598–600, 2009.

Bellido, J. L., Tulonen, T., Kankaala, P., and Ojala, A.: CO(2) and CH(4) fluxes during spring and autumn mixing periods in a boreal lake (Paajarvi, southern Finland), *J. Geophys. Res.-Biogeo.*, 114, G04007, doi:10.1029/2009JG000923, 2009.

Boereboom, T., Depoorter, M., Coppens, S., and Tison, J.-L.: Gas properties of winter lake ice in Northern Sweden: implication for carbon gas release, *Biogeosciences*, 9, 827–838, doi:10.5194/bg-9-827-2012, 2012.

Boon, P. I. and Mitchell, A.: Methanogenesis in the sediments of an australian fresh-water wetland-comparison with aerobic decay, and factors controlling methanogenesis, *Fems Microbiol. Ecol.*, 18, 175–190, 1995.

Borrel, G., Jezequel, D., Biderre-Petit, C., Morel-Desrosiers, N., Morel, J. P., Peyret, P., Fonty, G., and Lehours, A. C.: Production and consumption of methane in freshwater lake ecosystems, *Res. Microbiol.*, 162, 832–847, 2011.

Brosius, L. S., Walter Anthony, K. M., Grosse, G., Chanton, J. P., Farquharson, L. M., Overduin, P. P., and Meyer, H.: Using the deuterium isotope composition of permafrost meltwater to constrain thermokarst lake contributions to atmospheric CH₄ during the last deglaciation, *J. Geophys. Res.-Biogeo.*, 117, G01022, doi:10.1029/2011JG001810, 2012.

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- Carlson, R. E.: Trophic state index for lakes, *Limnol. Oceanogr.*, 22, 361–369, 1977.
- Casper, P., Marbely, S. C., Hall, G. H., and Finlay, B. J.: Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere, *Biogeochemistry*, 49, 1–19, 2000.
- Clilverd, H., White, D., and Lilly, M.: Chemical and physical controls on the oxygen regime of ice-covered arctic lakes and reservoirs, *J. Am. Water Resour. As.*, 45, 500–511, 2009.
- Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J.: Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget, *Ecosystems*, 10, 171–184, 2007.
- Conrad, R., Claus, P., and Casper, P.: Stable isotope fractionation during the methanogenic degradation of organic matter in the sediment of an acidic bog lake, Lake Grosse Fuchskuhle, *Limnol. Oceanogr.*, 55, 1932–1942, 2010.
- Dean, W. E.: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods, *J. Sediment. Res.*, 44, 242–248, 1974.
- Downing, J. A., Prairie, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., Striegl, R. G., McDowell, W. H., Kortelainen, P., Caraco, N. F., Melack, J. M., and Middelburg, J. J.: The global abundance and size distribution of lakes, ponds, and impoundments, *Limnol. Oceanogr.*, 51, 2388–2397, 2006.
- Dunfield, P., Knowles, R., Dumont, R., and Moore, T. R.: Methane production and consumption in temperate and sub-arctic peat soils-response to temperature and pH, *Soil Biol. Biochem.*, 25, 321–326, 1993.
- Dzyuban, A. N.: Dynamics of microbial oxidation of methane in the water of stratified lakes, *Microbiology* 79, 822–829, 2010.
- Giblin, A., Luecke, C., Kling, G., and White, D.: Nutrient and chemical data for various lakes near Toolik Research Station, Arctic LTER, Summer 2009, Long Term Ecological Research Network, available at: <http://dx.doi.org/10.6073/pasta/1b77f4c8d8cc250ce0f90bbb17d9c976>, 2009.
- Gow, A. J. and Langston, D.: Growth History of Lake Ice in Relation to its Stratigraphic, Crystalline and Mechanical Structure, US Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 24 pp., 1977.
- Graneli, W., Lindell, M., and Tranvik, L.: Photo-oxidative production of dissolved inorganic carbon in lakes of different humic content, *Limnol. Oceanogr.*, 41, 698–706, 1996.

CH₄ and CO₂ emissions from Alaskan lakes

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Greene, S., Walter Anthony, K. M., Archer, D., Sepulveda-Jauregui, A., and Martinez-Cruz, K.: Modeling the impediment of methane ebullition bubbles by seasonal lake ice, *Biogeosciences Discuss.*, 11, 10863–10916, doi:10.5194/bgd-11-10863-2014, 2014.

Gregory-Eaves, I., Smol, J. P., Finney, B. P., Lean, D. R. S., and Edwards, M. E.: Characteristics and variation in lakes along a north-south transect in Alaska, *Arch. Hydrobiol.*, 147, 193–223, 2000.

Grosse, G., Jones, B., and Arp, C.: Thermokarst lakes, drainage, and drained basins, *Treatise Geomorph.*, 8, 325–353, 2013.

Guerin, F. and Abril, G.: Significance of pelagic aerobic methane oxidation in the methane and carbon budget of a tropical reservoir, *J. Geophys. Res.-Biogeo.*, 112, G03006, doi:10.1029/2006JG000393, 2007.

Jorgenson, T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., and Jones, B.: Permafrost Characteristics of Alaska, Institute of Northern Engineering, University of Alaska Fairbanks NICOP, University of Alaska Fairbanks, USA, 2008.

Juutinen, S., Rantakari, M., Kortelainen, P., Huttunen, J. T., Larmola, T., Alm, J., Silvola, J., and Martikainen, P. J.: Methane dynamics in different boreal lake types, *Biogeosciences*, 6, 209–223, doi:10.5194/bg-6-209-2009, 2009.

Kanevskiy, M., Shur, Y., Fortier, D., Jorgenson, M. T., and Stephani, E.: Cryostratigraphy of late Pleistocene syngenetic permafrost (yedoma) in northern Alaska, Itkillik River exposure, *Quaternary Res.*, 75, 584–596, 2011.

Karlstrom, T. W., Coulter, H. W., Fernald, A. T., Williams, J. R., Hopkins, D. M., Pewe, T. L., Drewes, H., Muller, E. H., and Condon, W. H.: *Surficial Geology of Alaska, Interior*, USD.o., Alaska, USA, 1964.

Kessler, M. A., Plug, L., and Walter Anthony, K. M.: Simulating the decadal to millennial scale dynamics of morphology and sequestered carbon mobilization of two thermokarst lakes in N. W. Alaska, *J. Geophys. Res.*, 117, G00M06, doi:10.1029/2011JG001796, 2012.

Kling, G. W.: *Field and Lab Methods and Protocols*, Protocol version: v2.8, Kling Lab University of Michigan, 2010.

Kling, G. W., Kipphut, G. W., and Miller, M. C.: Arctic lakes and streams as gas conduits to the atmosphere - implications for tundra carbon budgets, *Science* 251, 298–301, 1991.

Kling, G. W., Kipphut, G. W., and Miller, M. C.: The flux of CO₂ and CH₄ from lakes and rivers in arctic Alaska, *Hydrobiologia*, 240, 23–36, 1992.

CH₄ and CO₂ emissions from Alaskan lakes

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Langer, M., Westermann, S., Walter Anthony, K. M., Wischnewski, K., and Boike, J.: Frozen ponds: production and storage of methane during the Arctic winter in a lowland tundra landscape in northern Siberia, *Lena River Delta, Biogeosciences Discuss.*, 11, 11061–11094, doi:10.5194/bgd-11-11061-2014, 2014.

5 Maberly, S. C., Barker, P. A., Stott, A. W., and De Ville, M. M.: Catchment productivity controls CO₂ emissions from lakes, *Nat. Clim. Change*, 3, 391–394, 2013.

Madigan, M. T., Martinko, J. M., Dunlap, P. V., and Clark, D. P.: *Brock Biology of Microorganisms*, 12 edn. Pearson education, 2009.

10 Marotta, H., Pinho L., Bastviken D., Tranvik L. J., and Enrich-Prast, A.: Greenhouse gas production in low-latitude lake sediments responds strongly to warming, *Nat. Clim. Change*, 4, 467–470, 2014.

Martens, C. S., Kelley, C. A., Chanton, J. P., and Showers, W. J.: Carbon and hydrogen isotopic characterization of methane from wetlands and lakes of the Yukon-Kuskokwim Delta, Western Alaska, *J. Geophys. Res.-Atmos.*, 97, 16689–16701, 1992.

15 Martinez-Cruz, K., Sepulveda-Jauregui, A., Walter Anthony, K. M., and Thalasso, F.: Latitudinal and seasonal variation of aerobic methane oxidation in Alaskan lakes, *Biogeosciences*, in preparation, 2014.

Michmerhuizen, C. M., Striegl, R. G., and McDonald, M. E.: Potential methane emission from north-temperate lakes following ice melt, *Limnol. Oceanogr.*, 41, 985–991, 1996.

20 Myhre, G., Shindell, D., Breon, F. M., Collins, W., Fuglestedt, J., Huang, J., Koch, D., Lamarque, J. F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and natural radiative forcing, in: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

25 National Institute of Standards and Technology (NIST): *NIST Chemistry Web Book*, 2011.

Nguyen, T. D., Crill, P., and Bastviken, D.: Implications of temperature and sediment characteristics on methane formation and oxidation in lake sediments, *Biogeochemistry*, 100, 185–196, 2010.

30 Phelps, A. R., Peterson, K. M., and Jeffries, M. O.: Methane efflux from high-latitude lakes during spring ice melt, *J. Geophys. Res.-Atmos.*, 103, 29029–29036, 1998.

CH₄ and CO₂ emissions from Alaskan lakes

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Ping, C. L., Michaelson, G. J., Jorgenson, M. T., Kimble, J. M., Epstein, H., Romanovsky, V. E., and Walker, D. A.: High stocks of soil organic carbon in the North American Arctic region, *Nat. Geosci.*, 1, 615–619, 2008.

Repo, M. E., Huttunen, J. T., Naumov, A. V., Chichulin, A. V., Lapshina, E. D., Bleuten, W., and Martinkainen, P. J.: Release of CO₂ and CH₄ from small wetland lakes in western Siberia, *Tellus B*, 59, 788–796, 2007.

Schulz, S., Matsuyama, H., and Conrad, R.: Temperature dependence of methane production from different precursors in a profundal sediment (Lake Constance), *Fems Microbiol. Ecol.*, 22, 207–213, 1997.

Semiletov, I. P., Pipko, I. I., Pivovarov, N. Y., Popov, V. V., Zimov, S. A., Voropaev, Y. V., and Daviodov, S. P.: Atmospheric carbon emission from North Asian Lakes: A factor of global significance, *Atmos. Environ.*, 30, 1657–1671, 1996.

Sepulveda-Jauregui, A., Martinez-Cruz, K., Strohm, A., Walter Anthony, K. M., and Thalasso, F.: A new method for field measurement of dissolved methane in water using infrared tunable diode laser absorption spectroscopy, *Limnol. Oceanogr.-Meth.*, 10, 560–567, 2012.

Smith, L. C., Sheng, Y. W., and MacDonald, G. M.: A first pan-Arctic assessment of the influence of glaciation, permafrost, topography and peatlands on Northern Hemisphere lake distribution, *Permafrost Periglac.*, 18, 201–208, 2007.

Striegl, R. G. and Michmerhuizen, C. M.: Hydrologic influence on methane and carbon dioxide dynamics at two north-central Minnesota lakes, *Limnol. Oceanogr.*, 43, 1519–1529, 1998.

Tan, Z., Zhuang, Q., and Walter Anthony, K. M.: Modeling methane emissions from Arctic lakes: Model development and site-level study, *J. Adv. Model Earth Sy.*, in review, 2014.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, *Global Biogeochem. Cy.*, 23, GB2023, doi:10.1029/2008GB003327, 2009.

Thauer, R. K., Kaster, A. K., Seedorf, H., Buckel, W., and Hedderich, R.: Methanogenic archaea: ecologically relevant differences in energy conservation, *Nat. Rev. Microbiol.*, 6, 579–591, 2008.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., Dillon, P., Finlay, K., Fortino, K., Knoll, L. B., Kortelainen, P. L., Kutser, T., Larsen, S., Laurion, I., Leech, D. M., McCallister, S. L., McKnight, D. M., Melack, J. M., Overholt, E., Porter, J. A., Prairie, Y., Renwick, W. H., Roland, F., Sherman, B. S., Schindler, D. W., Sobek, S., Tremblay, A., Vanni, M. J., Verschoor, A. M., von Wachenfeldt, E., and Weyhenmeyer, G. A.:

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Lakes and reservoirs as regulators of carbon cycling and climate, *Limnol. Oceanogr.*, 54, 2298–2314, 2009.

Utsumi, M., Nojiri, Y., Nakamura, T., Nozawa, T., Otsuki, A., Takamura, N., Watanabe, M., and Seki, H.: Dynamics of dissolved methane and methane oxidation in dimictic Lake Nojiri during winter, *Limnol. Oceanogr.*, 43, 10–17, 1998.

Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D., and Chapin, F. S.: Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming, *Nature*, 443, 71–75, 2006.

Walter, K. M., Engram, M., Duguay, C. R., Jeffries, M. O., and Chapin, F. S.: The potential use of synthetic aperture radar for estimating methane ebullition from Arctic lake, *J. Am. Water Resour. As.*, 44, 305–315, 2008.

Walter Anthony, K. M., Vas, D. A., Brosius, L., Chapin, F. S., Zimov, S. A., and Zhuang, Q. L.: Estimating methane emissions from northern lakes using ice-bubble surveys, *Limnol. Oceanogr.-Meth.*, 8, 592–609, 2010.

Walter Anthony, K. M., Anthony, P., Grosse, G., and Chanton, J.: Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers, *Nat. Geosci.*, 5, 419–426, 2012.

Walter Anthony, K. M., and Anthony, P.: Constraining spatial variability of methane ebullition seeps in thermokarst lakes using point process models, *J. Geophys. Res.-Biogeo.*, 118, 1015–1034, 2013.

Walter Anthony, K. M., Zimov, S. A., Grosse, G., Jones, M. C., Anthony, P., Chapin III, F. S., Finlay, J. C., Mack, M. C., Davydov, S., Frenzel, P., and Frohling S.: A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch, *Nature*, 511, 452–456, doi:10.1038/nature13560, 2014.

Welch, H. E., Legault, J. A., and Bergmann, M. A.: Effects of snow and ice on the annual cycles of heat and light in Saqvaqjuac Lakes, *Can. J. Fish. Aquat. Sci.*, 44, 1451–1461, 1987.

West, J. J. and Plug, L. J.: Time-dependent morphology of thaw lakes and taliks in deep and shallow ground ice, *J. Geophys. Res.-Earth*, 113, 14, F01009, doi:10.1029/2006JF000696, 2008.

Wetzel, R. G.: *Limnology: Lake and River Ecosystems*, Academic Press Elsevier, San Diego, California, USA, 2001.

White, D. M., Ciliverd, H. M., Tidwell, A. C., Little, L., Lilly, M. R., Chambers, M., and Reichardt, D.: A tool for modeling the winter oxygen depletion rate in arctic lakes, *J. Am. Water Resour. As.*, 44, 293–304, 2008.

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Wilhelm, E., Battino, R., and Wilcock, R. J.: Low-pressure solubility of gases in liquid water, *Chem. Rev.*, 77, 219–262, 1977.

Yvon-Durocher, G., Allen, A. P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., Thanh-Duc, N., and del Giorgio, P. A.: Methane fluxes show consistent temperature dependence across microbial to ecosystem scales, *Nature*, 507, 488–491, 2014.

Zhuang, Q., Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Prinn, R. G., Steudler, P. A., Felzer, B. S., and Hu, S.: Net emissions of CH₄ and CO₂ in Alaska: implications for the region's greenhouse gas budget, *Ecol. Appl.*, 17, 203–212, 2007.

Zimov, S. A., Voropaev, Y. V., Semiletov, I. P., Davidov, S. P., Prosiannikov, S. F., Chapin, F. S., Chapin, M. C., Trumbore, S., and Tyler, S.: North Siberian lakes: a methane source fueled by Pleistocene carbon, *Science*, 277, 800–802, 1997.

Zimov, S. A., Voropaev, Y. V., Davydov, S. P., Zimova, G. M., Davydova, A. I., Chapin III, F. S., and Chapin, M. C.: Flux of methane from north Siberian aquatic systems: Influence on atmospheric methane, in: *Permafrost Response on Economic Development, Environmental Security and Natural Resources*, NATO Science Series 2, 76, edited by: Paepe, R. and Melnikov, V. P., Kluwer Academic Publishers, Dordrecht, Netherlands, Boston, Massachusetts, USA, 511–524, 2001.

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Table 1. Lake physical and chemical properties from 40 Alaskan lakes. *N* – Lake number; * indicates informal lake names, the A-number refers to lake identification numbers used by Gregory Eaves et al. (2000) for study of the same lakes; Y/NY – permafrost soil type as Yedoma or non-Yedoma^{a,b}; TSI – Trophic State Index^c; EC – Ecozonal Categories^d; Lat – Latitude; Long – Longitude; DN^e – Sedimentary Deposit Name^e; MD – Maximum known depth; A – Area; SecD – Secchi Depth; *T* (Win) Winter temperature; *T* (Sum) Summer temperature; pH (Win) – Winter; pH (Sum) – Summer; ORP (Win) – Winter redox potential average; ORP (Sum) – Summer redox potential; Chl *a*-Summer surface chlorophyll *a*; PO₄³⁻ – Dissolved phosphate; NO₃⁻ – Nitrate; SO₄²⁻ – Sulfate; TOC – Total Organic Carbon; TN – Total Nitrogen; TOCS- Total organic carbon in surface sediments; TNS-Total nitrogen in surface sediments. Water column-averages are reported for temperature, pH and ORP. Water-column carbon and nutrient values are from 1 m depth, except data summarized from other investigators^{g,h}. Error terms are the standard deviation. ND indicates not determined; CF indicates lake completely frozen; “<” indicates below detection limit, “–” indicates no standard deviation due a sample size of one.

<i>N</i>	Name	Y/nY ^b	TSI ^c	EC ^d	Lat (° N)	Long (° W)	DN ^e	MD (m)	A (km ²)	SecD (m)	<i>T</i> (Win) (°C)	<i>T</i> (Sum) (°C)
1	Big Sky* A31	NY	O	ArT	69.581	148.639	ES	2.2	0.349	1.30	0.7 ± 0.2	15.7 ± 0.9
2	Dragon's Pond* A33	NY	O	ArT	68.795	148.843	GF	1.5	0.010	1.30	2.4 ^f ± 2.2	18.4 ± 0.9
3	GTH 112	NY	D, M	ArT	68.672	149.249	GF	4.8	0.025	0.80	2.6 ^f ± 1.1	11.7 ± 3.8
4	NE2	NY	O	ArT	68.647	149.582	GMD	2.7	0.067	2.70	0.4 ± 0.6	15.3 ± 0.6
5	E6	NY	O	ArT	68.643	149.440	GMD	2.6	0.027	2.60	3.3 ^f ± 1.5	15.8 ± 1.0
6	E5 Oil Spill A30	NY	O	ArT	68.642	149.458	GMD	11.9	0.116	3.10	2.8 ^f ± 1.3	10.8 ± 4.2
7	Toolik A28	NY	UO	ArT	68.632	149.605	GMD	24.1	1.449	3.31	2.2 ± 1.1	10.3 ± 4.1
8	E1	NY	UO	ArT	68.626	149.555	GMD	6.4	0.026	2.55	2.4 ± 0.8	12.4 ± 3.7
9	Autumn* A35	NY	UO	ArT	68.462	149.393	GMD	7.5	0.057	4.51	0.45 ^f ± 4.4	13.5 ± 1.9
10	Julietta* A27	NY	UO	ArT	68.447	149.369	GMD	7.0	0.051	3.40	-1.4 ^f ± 2.0	14.3 ± 1.2
11	El Fuego* A36	NY	UO	FoT	67.666	149.716	GMD	2.5	0.057	2.71	2.9 ^f ± 4.5	15.7 ± 1.2
12	Jonas* A26	NY	UO	FoT	67.647	149.722	GMD	4.2	0.170	0.95	-0.2 ± 0.0	14.2 ± 4.8
13	Augustine Zoli* A25	NY	O	FoT	67.138	150.349	F	3.0	0.069	1.12	ND	17.3 ± 1.7
14	Ping*	NY	UO	FoT	67.136	150.370	F	1.4	0.102	1.08	0.1 ± 0.3	18.5 ± 1.7
15	Grayling A24	NY	O	FoT	66.954	150.393	MAC	1.8	0.401	1.80	0.4 ± 0.1	17.0 ± 0.8
16	Eugenia*	Y	D, M	FoT	65.834	149.631	ES	3.3	0.027	0.70	0.5 ± 0.7	17.0 ± 4.0
17	Vault*	Y	D, O	NBF	65.029	147.699	MAC	3.7	0.003	1.00	0.3 ± 0.3	9.5 ± 7.7
18	Goldstream*	Y	D, M	NBF	64.916	147.847	E	3.3	0.010	1.00	1.5 ± 1.5	9.3 ± 6.9
19	Doughnut ^a	NY	O	NBF	64.899	147.908	E	3.8	0.035	1.59	0.7 ± 0.8	22.2 ± 2.2

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Table 1. Continued.

N	Name	Y/nY ^b	TSJ ^c	EC ^d	Lat (° N)	Long (° W)	DN ^e	MD (m)	A (km ²)	SecD (m)	T (Win) (°C)	T (Sum) (°C)
20	Killarney*	Y	D, M	NBF	64.870	147.901	E	2.1	0.008	0.50	0.6 ± 0.7	7.8 ± 4.5
21	Smith A13 ^a	NY	D, E	NBF	64.865	147.868	E	4.4	0.094	0.50	0.5 ± 0.7	19.0 ± 1.7
22	Stevens Pond*	Y	D, M	NBF	64.863	147.871	E	1.1	0.002	0.50	CF	17.6 ± 1.6
23	Duece A2	Y	D, UO	NBF	64.863	147.942	E	6.0	0.023	0.79	0.9 ± 0.6	11.4 ± 7.0
24	Ace A1	Y	D, M	NBF	64.862	147.937	E	9.0	0.077	1.26	2.9 ± 0.9	11.6 ± 6.3
25	Rosie Creek*	Y	D, O	NBF	64.770	148.079	E	3.7	0.004	1.46	0.0 ± 0.3	11.9 ± 2.4
26	Monasta A37 ^b	NY	D, UO	NBF	64.741	148.276	MAC	5.6	0.005	0.43	ND	8.8 ± 5.6
27	91 Lake*	NY	O	NBF	63.848	148.973	F	0.5	0.066	1.40	ND	15.3 ± 0.7
28	Otto	NY	O	FoT	63.842	149.037	GMD	3.1	0.515	1.60	1.6 ± 1.3	12.0 ± 6.4
29	Floatplane* A16	NY	O	FoT	63.394	148.670	GL	5.0	0.103	1.20	3.9 ^f ± 1.5	13.1 ± 1.3
30	Nutella* A39	NY	O	AIT	63.215	147.678	I	9.4	0.020	3.10	3.4 ^f ± 1.1	10.2 ± 3.4
31	Swampbuggy A18	NY	O	FoT	63.055	147.421	GL	4.9	0.142	1.20	3.2 ^f ± 2.3	13.7 ± 0.4
32	Montana A40	NY	O	SBF	62.143	150.048	F	9.0	0.300	2.80	0.8 ± 0.7	16.2 ± 2.4
33	Rainbow Shore* A41	NY	M	SBF	61.694	150.089	GL	11.5	0.575	2.00	0.9 ± 1.0	17.2 ± 1.8
34	Big Merganser A49	NY	O	SBF	60.726	150.644	GL	24.2	0.210	2.00	2.9 ± 1.3	14.4 ± 4.7
35	Rainbow A48	NY	UO	SBF	60.719	150.808	GMD	5.5	0.630	3.00	1.7 ± 1.6	14.8 ± 5.6
36	Dolly Varden A47	NY	UO	SBF	60.704	150.787	GL	30.0	1.074	11.00	2.5 ± 0.2	17.1 ± 0.6
37	Abandoned Cabin* A50	NY	O	SBF	60.696	151.315	GL	3.0	0.031	3.00	1.9 ^f ± 1.6	17.4 ± 1.7
38	Scout A46	NY	O	SBF	60.533	150.843	GL	6.3	0.384	4.00	0.7 ± 0.7	16.4 ± 1.7
39	Engineer A45	NY	O	SBF	60.478	150.323	GMD	3.9	0.909	1.60	0.4 ± 0.6	16.4 ± 1.2
40	Lower Ohmer A44	NY	O	SBF	60.456	150.317	GMD	28.0	0.471	2.70	3.6 ^f ± 0.5	11.6 ± 3.7
	Yedoma ⁱ	–	–	–	–	–	–	4.1 ^k	0.022 ^k	0.82 ^k	1.1 ^k ± 1.0	11.3 ^k ± 4.5
	Non-Yedoma ^l	–	–	–	–	–	–	7.6 ^k	0.267 ^l	2.39 ^l	1.6 ^k ± 1.3	14.9 ^l ± 3.0

Table 1. Continued.

N	Name	pH (Win)	pH (Sum)	ORP (Win) (mV)	ORP (Sum) (mV)	Chl <i>a</i> ($\mu\text{g L}^{-1}$)	PO ₄ ³⁻ ($\mu\text{g L}^{-1}$)	NO ₃ ⁻ (mg L ⁻¹)
1	Big Sky [†] A31	7.0 ± 0.0	8.8 ± 0.7	102 ± 18	254 ± 78	2.6 ± 3.3	4.2 ^g	< 0.01
2	Dragon's Pond [†] A33	ND	7.7 ± 0.5	ND	304 ± 78	4.7 ± 4.2	5.9 ^g	ND
3	GTH 112	ND	7.2 ± 0.7	ND	264 ± 69	45.9 ± 7.4	ND	< 0.01
4	NE2	6.6 ± 0.1	7.9 ± 0.6	322 ± 17	299 ± 66	3.7 ± 4.6	1.3 ^h	ND
5	E6	ND	7.7 ± 0.7	ND	272 ± 80	5.9 ± 6.2	1.1 ^h	ND
6	E5 Oil Spill A30	ND	7.1 ± 0.8	ND	322 ± 64	13.5 ± 2.9	1.8 ^h	ND
7	Toolik A28	6.9 ± 0.1	7.9 ± 0.8	303 ± 32	308 ± 75	1.5 ± 0.4	1.6 ^h	< 0.01
8	E1	7.0 ± 0.1	9.1 ± 0.4	283 ± 58	231 ± 71	1.3 ^g ± -	1.1 ^h	< 0.01
9	Autumn [†] A35	ND	8.2 ± 0.6	ND	303 ± 45	2.9 ± 2.4	2.8 ^g	ND
10	Julietta [†] A27	ND	8.5 ± 0.6	ND	318 ± 34	3.4 ± 3.8	3.6 ^g	< 0.01
11	El Fuego [†] A36	ND	8.8 ± 0.4	ND	271 ± 50	1.2 ± 0.1	ND	ND
12	Jonas [†] A26	8.2 ± 0.0	8.5 ± 0.6	23 ± 4	250 ± 119	1.0 ± 0.0	6.6 ^g	0.02
13	Augustine Zoli [†] A25	ND	8.7 ± 0.6	ND	259 ± 80	10.1 ± 11.4	9.8 ^g	< 0.01
14	Ping [†]	5.9 ± 0.0	6.9 ± 0.2	211 ± 6	303 ± 21	22.4 ± 0.0	ND	< 0.01
15	Grayling A24	6.3 ± 0.0	7.6 ± 0.5	119 ± 4	323 ± 66	20.7 ± 20.5	5.3	< 0.01
16	Eugenia [†]	6.3 ± 0.0	7.0 ± 0.3	118 ± 9	314 ± 45	41.9 ± 2.4	ND	< 0.01
17	Vault [†]	7.7 ± 0.7	8.6 ± 0.8	75 ± 62	156 ± 87	35.0 ± 15.0	ND	ND
18	Goldstream [†]	7.4 ± 0.6	7.9 ± 0.7	117 ± 118	216 ± 134	31.0 ± 14.5	9.7	0.01
19	Doughnut ^{†a}	6.8 ± 0.1	7.7 ± 0.6	189 ± 56	254 ± 77	113.4 ± 0.0	ND	ND
20	Killarney [†]	7.0 ± 0.1	7.6 ± 0.7	66 ± 45	316 ± 99	ND	10.2	0.01
21	Smith A13 ^{†a}	6.5 ± 0.0	8.3 ± 1.1	98 ± 16	187 ± 99	44.7 ± 0.6	16.2 ^g	< 0.01
22	Stevens Pond [†]	CF	8.4 ± 1.7	CF	212 ± 136	43.7 ± 13.4	CF	CF
23	Ducee A2	7.2 ± 0.0	9.2 ± 0.4	58 ± 10	-20 ± 94	1.5 ^g ± -	60.2 ^g	0.32
24	Ace A1	7.1 ± 0.0	8.1 ± 1.0	68 ± 15	116 ± 161	54.0 ^g ± -	31.5 ^g	0.02
25	Rosie Creek [†]	7.1 ± 0.0	8.1 ± 1.0	33 ± 19	245 ± 127	45.3 ± 1.9	ND	ND
26	Monasta A37 ^{†a}	ND	6.3 ± 0.1	ND	160 ± 119	ND	24.9 ^g	ND
27	91 Lake [†]	ND	8.2 ± 0.0	ND	351 ± 25	ND	ND	ND
28	Otto	7.1 ± 0.1	7.8 ± 0.5	120 ± 141	260 ± 59	8.2 ± 11.6	9.8	0.01
29	Floatplane [†] A16	ND	8.1 ± 0.5	ND	349 ± 25	27.1 ± 1.3	4.3 ^g	ND
30	Nutella [†] A39	ND	7.2 ± 0.3	ND	384 ± 20	13.6 ± 1.4	3.3 ^g	ND
31	Swampbuggy A18	ND	7.3 ± 0.0	ND	362 ± 1	7.9 ± 0.9	4.7 ^g	ND
32	Montana A40	6.1 ± 0.0	7.1 ± 0.4	290 ± 31	329 ± 61	9.5 ± 0.4	2.2 ^g	< 0.01
33	Rainbow Shore [†] A41	6.5 ± 0.3	7.9 ± 0.4	289 ± 12	305 ± 49	7.2 ± 0.9	4.7 ^g	0.02
34	Big Merganser A49	6.4 ± 0.4	7.1 ± 0.3	321 ± 38	325 ± 49	7.4 ± 1.1	4.4 ^g	< 0.01
35	Rainbow A48	7.0 ± 0.0	7.7 ± 0.6	241 ± 62	289 ± 85	12.6 ± 0.4	4.8 ^g	< 0.01
36	Dolly Varden A47	ND	7.1 ± 0.3	ND	282 ± 22	3.7 ± 0.5	2.1 ^g	< 0.01
37	Abandoned Cabin [†] A50	6.0 ± 0.5	6.3 ± 0.2	299 ± 113	338 ± 33	10.2 ± 1.1	2.3 ^g	0.04
38	Scout A46	6.3 ± 0.4	7.0 ± 0.4	290 ± 36	347 ± 25	10.9 ± 0.4	4.7 ^g	0.01
39	Engineer A45	6.7 ± 0.3	7.8 ± 0.4	273 ± 31	267 ± 43	7.0 ± 0.2	7.5 ^g	< 0.01
40	Lower Ohmer A44	ND	7.5 ± 0.5	ND	379 ± 50	9.9 ± 0.5	1.8 ^g	< 0.01
	Yedomal [†]	7.1 ^k ± 0.5	8.2 ^k ± 0.9	84 ^k ± 27	187 ^k ± 118	34.5 ^k ± 18.0	27.9 ^k	0.09 ^k
	Non-Yedomal [†]	6.7 ^l ± 0.5	7.7 ^k ± 0.7	222 ^l ± 95	295 ^l ± 51	14.5 ^l ± 21.8	5.3 ^l	0.02 ^k

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Table 1. Continued.

<i>N</i>	Name	SO ₄ ²⁻ (mg L ⁻¹)	TOC (mg L ⁻¹)	TN (mg L ⁻¹)	TOCS (%)	TNS (%)
1	Big Sky* A31	< 0.04	16.48	1.3	1.8 ± 0.0	1.5 ± 0.3
2	Dragon's Pond* A33	6.20 ^g	16.98	3.2	6.2 ± 0.8	2.2 ± 0.3
3	GTH 112	0.51	ND	ND	ND	ND
4	NE2	ND	0.93	0.2	2.9 ± 0.5	1.1 ± 0.2
5	E6	ND	ND	ND	3.5 ± 0.5	1.4 ± 0.1
6	E5 Oil Spill A30	< 0.04	ND	0.2 ^g	8.1 ± 0.1	0.7 ± 0.0
7	Toolik A28	< 0.04	0.70	0.2	7.8 ± 1.3	0.8 ± 0.2
8	E1	< 0.04	0.18	0.2	ND	ND
9	Autumn* A35	5.30 ^g	3.66	0.4	ND	ND
10	Julieta* A27	< 0.04	0.71	0.3 ^g	0.8 ± 0.8	0.4 ± 0.2
11	El Fuego* A36	40.40 ^g	ND	0.4	1.1 ± 0.2	0.5 ± 0.1
12	Jonas* A26	0.25	0.89	0.7	2.9 ± 2.2	1.1 ± 0.8
13	Augustine Zoli* A25	< 0.04	4.42	0.9	3.0 ± 0.4	1.1 ± 0.1
14	Ping*	0.18	12.38	0.9	ND	ND
15	Grayling A24	0.86	8.34	1.0	7.3 ± 1.8	0.3 ± 0.1
16	Eugenia*	< 0.04	16.51	0.8	22.0 ± 0.3	ND
17	Vault*	ND	ND	ND	8.0 ± 1.2	ND
18	Goldstream*	0.30	45.30	3.0	4.2 ± 0.6	ND
19	Doughnut ^a	ND	ND	ND	24.0 ± 2.2	ND
20	Killarney*	0.01	18.12	2.3	3.5 ± 2.5	0.2 ± 0.1
21	Smith A13 ^a	11.60	ND	1.3 ^g	ND	ND
22	Stevens Pond*	CF	CF	CF	CF	CF
23	Duece A2	1.10	ND	2.4 ^g	5.0 ± 0.7	1.8 ± 0.7
24	Ace A1	0.34	ND	1.3 ^g	2.6 ± 2.5	1.0 ± 0.9
25	Rosie Creek*	ND	ND	ND	ND	ND
26	Monasta A37 ^a	ND	58.80 ^g	2.2 ^g	ND	ND
27	91 Lake*	ND	ND	ND	ND	ND
28	Otto	0.20	3.63	0.8	8.8 ± 1.3	ND
29	Floatplane* A16	ND	ND	0.5 ^g	ND	ND

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Table 1. Continued.

N	Name	SO ₄ ²⁻ (mg L ⁻¹)	TOC (mg L ⁻¹)	TN (mg L ⁻¹)	TOCS (%)	TNS (%)
30	Nutella ^a A39	ND	ND	0.3 ^g	ND	ND
31	Swampbuggy A18	ND	ND	0.3 ^g	ND	ND
32	Montana A40	< 0.04	0.16	0.3	ND	ND
33	Rainbow Shore ^a A41	0.33	52.20	0.1	38.8 ± 15.2	ND
34	Big Merganser A49	12.32	2.38	0.3	ND	ND
35	Rainbow A48	2.30	1.05	0.2	ND	ND
36	Dolly Varden A47	1.70	ND	0.2 ^g	6.2 ± 0.7	ND
37	Abandoned Cabin ^a A50	0.76	ND	0.3 ^g	25.7 ± 0.4	ND
38	Scout A46	0.78	2.58	0.4	23.0 ± 0.1	ND
39	Engineer A45	< 0.04	5.71	0.6	7.6 ± 1.2	ND
40	Lower Ohmer A44	2.50	ND	0.3 ^g	ND	ND
	Yedoma ⁱ	0.44 ^k	26.6 ^k	2.0 ^k	7.6 ^k ± 7.3	1.0 ^k ± 0.8
	Non-Yedoma ^j	5.39 ^k	10.1 ^l	0.6 ^l	10.0 ^k ± 10.6	1.0 ^k ± 0.6

^a Doughnut L., a partially-drained lake (uncalibrated ¹⁴C age 1190 ± 20 yr BP, measured on outer wood of an in situ, dead tree near the lake center), Smith L., and Monasta L. were included in the non-yedoma lake classification. While Doughnut and Monasta lakes likely formed in yedoma permafrost originally, following partial drainage events, they no longer appear to be influenced by active yedoma thaw along the margin. Smith Lake is thought to have formed as part of a previous river drainage network (V. Alexander, personal communication, 2011).

^b Permafrost soil type: Y – Yedoma, NY – Non yedoma.

^c Trophic State Index: UO – Ultraoligotrophic, O – Oligotrophic, M – Mesotrophic, E – Eutrophic, D – Dystrophic.

^d Ecozonal categories according to Gregory Eaves et al. (2000): ArT – Arctic tundra, AlT – Alpine tundra, FoT – Forest tundra, NBF – Northern boreal forest, SBF – Southern boreal forest.

^e Deposit Name: ES – Eolian silt, GF – Glaciofluvial, GMD – old Glacial moraines and drift, F – Fluvial, MAC – Mountain alluvium and colluvium, E – Eolian, GL – Glacio lacustrine (Jorgenson et al., 2008).

^f Winter (October–April) temperature average from Hobo measurements.

^g Data from Gregory Eaves et al. (2000).

^h Data from Giblin et al. (2009); water-column average.

ⁱ Average from yedoma lakes (Lake #25 excluded).

^j Average from non-yedoma lakes.

^{k,l} Different letters indicate a significant difference between yedoma and non-yedoma means.

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Table 2. Total annual CH₄ and CO₂ emissions by mode from 40 lakes along a north–south latitudinal transect in Alaska. * indicates informal lake names. Eb. Sum. – Direct Ebullition emission to the atmosphere from seeps during the ice-free summer season; Eb. Win. – Direct Ebullition emission to the atmosphere from seeps during the ice-cover winter season; IBS – Ice-bubble storage during spring ice melt; Stor. – Storage emission following ice-out; Diff. – Diffusive emission in summer, Total – Total annual emissions. If there was ND (no determination) for one or more modes in a lake, then total annual emission for the lake is likely an underestimate. Average emissions are summarized at the bottom of the table as is the percent of total annual emissions contributed by each mode as well as statistical results for differences in means among yedoma and non-yedoma lakes (Mann–Whitney test). Error terms represent standard deviation; *N* number of lakes analyzed; CF – Indicates impossible determination due to lake ice completely freezing to the lake bed in winter. CO₂ diffusive flux from lakes #17 and #18 were estimated from samples taken on multiple dates in June and July 2013 since no data were available in 2011–2012. Different letters^{a,b} indicate a significant difference between yedoma and non-yedoma means.

<i>N</i>	Lake name	CH ₄ (g m ⁻² yr ⁻¹)					Total
		Eb. Sum.	Eb. Win.	IBS	Diff.	Stor.	
1	Big Sky* A31	0.2	0.0	0.1	2.0	2.7	5.0
2	Dragon's Pond* A33	3.0	0.6	0.6	3.2	ND	7.4
3	GTH 112	ND	ND	ND	2.0	0.0	2.0
4	NE2	2.8	0.5	0.5	1.3	0.0	5.1
5	E6	8.8	1.6	1.9	1.0	ND	13.3
6	E5 Oil Spill A30	0.4	0.1	0.1	0.9	ND	1.4
7	Toolik A28	0.6	0.1	0.1	0.9	0.2	2.0
8	E1	5.1	0.9	0.9	2.5	0.0	9.4
9	Autumn* A35	6.9	1.3	1.5	1.0	ND	10.7
10	Julietta* A27	7.5	1.3	1.6	1.9	0.0	12.3
11	El Fuego* A36	10.2	2.0	2.2	ND	ND	14.5
12	Jonas* A26	7.0	1.3	1.4	ND	0.7	10.4
13	Augustine Zoli* A25	9.3	1.7	2.3	4.5	ND	17.7
14	Ping*	5.1	1.0	1.0	1.0	0.9	9.0
15	Grayling A24	1.9	0.4	0.6	2.1	0.0	5.0
16	Eugenia*	ND	ND	ND	6.6	0.6	7.2
17	Vault*	26.6	4.9	4.5	4.8	ND	40.9
18	Goldstream*	11.8	6.5	1.7	6.0	1.9	28.0
19	Doughnut *	ND	ND	ND	3.1	ND	3.1

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Table 2. Continued.

N	Lake name	Eb. Sum.	Eb. Win.	CH ₄ (g m ⁻² yr ⁻¹)		Stor.	Total
				IBS	Diff.		
20	Killarney*	20.7	4.1	14.0	4.4	ND	43.3
21	Smith A13	2.7	0.3	0.4	3.2	0.2	6.7
22	Stevens Pond*	55.0	12.8	8.1	3.1	CF	79.0
23	Duece A2	30.1	4.2	4.6	ND	ND	38.9
24	Ace A1	11.4	2.7	1.5	ND	ND	15.6
25	Rosie Creek*	80.1	17.4	20.5	160.3	39.0	317.4
26	Monasta A37	4.1	0.3	0.7	ND	ND	5.1
27	91 Lake*	1.5	0.2	0.2	2.3	ND	4.2
28	Otto	2.1	0.2	0.3	4.9	0.6	8.1
29	Floatplane* A16	ND	ND	ND	1.1	ND	1.1
30	Nutella* A39	0.1	0.0	0.0	1.1	ND	1.3
31	Swampbuggy A18	3.2	0.3	0.4	0.8	ND	4.8
32	Montana A40	4.1	0.2	0.3	3.5	0.0	8.1
33	Rainbow Shore* A41	3.9	0.2	0.3	ND	0.9	5.4
34	Big Merganser A49	0.5	0.0	0.0	1.8	0.1	2.5
35	Rainbow A48	15.1	0.8	1.3	ND	0.0	17.2
36	Dolly Varden A47	2.4	0.1	0.2	3.2	0.9	6.8
37	Abandoned Cabin* A50	0.4	0.0	0.0	ND	ND	0.5
38	Scout A46	ND	ND	ND	3.6	0.0	3.6
39	Engineer A45	0.0	0.0	0.0	4.9	0.0	4.9
40	Lower Ohmer A44	1.4	0.1	0.1	3.6	ND	5.3
Yedoma (mean ± SD)		25.9 ± 16.1 ^a	5.9 ± 3.6 ^a	5.7 ± 4.7 ^a	5.0 ± 1.4 ^a	1.2 ± 0.9 ^a	43.8 ± 17.3 ^a
Percent		59 %	13 %	13 %	11 %	3 %	100 %
Non-yedoma (mean ± SD)		4.0 ± 3.7 ^b	0.6 ± 0.6 ^b	0.7 ± 0.7 ^b	2.4 ± 1.3 ^b	0.4 ± 0.7 ^a	8.0 ± 4.1 ^b
Percent		50 %	7 %	9 %	30 %	5 %	100 %
All lakes (mean ± SD)						0.5 ± 0.7	

Table 2. Continued.

N	Lake name	CO ₂ (g m ⁻² yr ⁻¹)				Total
		Eb. Sum.	Eb. Win.	Diff.	Stor.	
1	Big Sky* A31	0.005	0.001	124	0	124.4
2	Dragon's Pond* A33	0.056	0.010	37	ND	37.1
3	GTH 112	ND	ND	42	ND	41.8
4	NE2	0.048	0.009	ND	ND	0.1
5	E6	0.153	0.028	36	ND	36.2
6	E5 Oil Spill A30	0.006	0.002	44	ND	44.3
7	Toolik A28	0.011	0.002	40	ND	40.5
8	E1	0.088	0.016	ND	ND	0.1
9	Autumn* A35	0.157	0.030	186	ND	186.5
10	Julietta* A27	0.128	0.023	270	ND	269.8
11	El Fuego* A36	0.181	0.036	ND	ND	0.2
12	Jonas* A26	0.122	0.023	ND	0	0.1
13	Augustine Zoli* A25	0.172	0.032	148	0	148.5
14	Ping*	0.097	0.018	34	0	34.2
15	Grayling A24	0.033	0.007	40	0	39.7
16	Eugenia*	ND	ND	131	ND	131.0
17	Vault*	0.445	0.099	1278	0	1279
18	Goldstream*	0.236	0.161	1582	0	1583
19	Doughnut*	ND	ND	ND	0	0.0
20	Killarney*	0.723	0.070	ND	0	0.8
21	Smith A13	0.052	0.006	251	0	250.9
22	Stevens Pond*	0.991	0.292	144	CF	144.9
23	Ducee A2	0.477	0.087	ND	0	0.6
24	Ace A1	0.196	0.059	ND	0	0.3
25	Rosie Creek*	1.462	0.404	1136	ND	1138
26	Monasta A37	0.076	0.005	ND	ND	0.1
27	91 Lake*	0.029	0.003	604	ND	604.2
28	Otto	0.040	0.004	234	0	233.9
29	Floatplane* A16	ND	ND	69	ND	69.5
30	Nutella* A39	0.002	0.000	ND	ND	0.0
31	Swampbuggy A18	0.056	0.006	ND	ND	0.1
32	Montana A40	0.076	0.004	143	33	176.4
33	Rainbow Shore* A41	0.075	0.004	ND	48	47.6
34	Big Merganser A49	0.010	0.001	59	ND	58.9
35	Rainbow A48	0.289	0.016	59	ND	59.4
36	Dolly Varden A47	0.047	0.003	65	ND	64.7
37	Abandoned Cabin* A50	0.008	0.000	85	52	137.5
38	Scout A46	ND	ND	64	0	63.9
39	Engineer A45	0.000	0.000	118	0	117.8
40	Lower Ohmer A44	0.027	0.001	157	ND	156.6
Yedoma (mean ± SD)		0.5 ± 0.3 ^a	0.13 ± 0.09 ^a	784 ± 757 ^a	0 ^a	784 ± 757 ^a
Percent		0.07 %	0.02 %	100 %	0 %	100 %
Non-yedoma (mean ± SD)		0.07 ± 0.07 ^b	0.01 ± 0.01 ^b	127 ± 127 ^b	10 ± 20 ^b	137 ± 129 ^b
Percent		0.05 %	0.01 %	92 %	7 %	100 %
All lakes (mean ± SD)					7 ± 17	159 ± 322

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Table 3. The Mann–Whitney and Kruskal–Wallis test results of the limnological and geographical characteristics of lakes using CH₄ or CO₂ emission mode as the factor. (≠) indicates a significant difference between limnological or geographical characteristic vs. flux; (=) indicates no significant difference at Z value < 1.96 . IBS – Ice-Bubble Storage; Latitude: I – interior, N – northern, S – southern according to Sect. 2.1; Permafrost Soil Type (Y – yedoma/YN – non-yedoma); Trophic State Index (TSI), Ecozonal Categories (EC), Deposit type (DN), according to descriptions in Table 1; Maximum depth known (MD) and Area (A). In the MD analysis we considered two categories: shallow lakes ≤ 2.5 m and deeper lakes > 2.5 m. In the A analysis we considered two categories: small lakes ≤ 0.1 km² and large lakes > 0.1 km².

Emission mode	Latitude	Y/NY	TS	EC	DN	MD	A
CH ₄							
Direct Ebullition (Summer)	I ≠ N-S	≠	O ≠ D-UO	NBF ≠ ArT-SBF	=	=	≠
Direct Ebullition (Winter)	S ≠ I-N	≠	O ≠ D-UO	SBF ≠ FoT-NBF	E ≠ GMD-GL	=	≠
IBS	S ≠ I-N	≠	O ≠ D-UO	SBF ≠ FoT-NBF	E ≠ GL	=	≠
Diffusion	I ≠ N	≠	D ≠ O-UO	ArT ≠ NBF-SBF	=	=	=
Storage	=	=	=	=	=	=	=
Total	I ≠ S	≠	O ≠ D-UO	=	GL ≠ E-GMD	=	≠
CO ₂							
Direct Ebullition (Summer)	I ≠ N-S	≠	O ≠ D-UO	NBF ≠ ArT-SBF	E ≠ GMD-GL	=	≠
Direct Ebullition (Winter)	S ≠ I-N	≠	O ≠ D-UO	SBF ≠ FoT-NBF	E ≠ GMD-GL	=	≠
Diffusion	I ≠ N	≠	=	NBF ≠ ArT-FoT-SBF	=	=	≠
Storage	=	=	=	=	=	=	=
Total	=	=	=	=	=	=	=

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Table 4. Single regression equations for emission modes based on data from Table 1.

Flux/Characteristic	Regression Equation	<i>n</i>	Adjusted <i>r</i> ²	<i>F</i>	<i>p</i>
CH ₄					
Direct Ebullition (summer)	Log(ES-CH4) = -0.50Log(Area)	32	0.30	14.4919	0.0006
Direct Ebullition (winter)	Log(EW-CH4) = -0.93 - 0.68Log(Area)	28	0.60	43.6036	0.0000
	Log(EW-CH4) = 0.10 - 1.12Log(SecD)	28	0.23	9.3352	0.0050
	Log(ES-CH4) = -2.63 + 0.81Log(TN)	24	0.32	12.4092	0.0018
IBS	Log(IFS-CH4) = -0.83 - 0.64Log(Area)	29	0.58	50.705	0.0001
	Log(IFS-CH4) = 0.10 - 1.00Log(SecD)	29	0.19	7.9309	0.0088
Diffusion	Log(DF-CH4) = 0.55Log(PO ₄ ⁻³)	24	0.40	16.7767	0.0004
Total	Log(Tot-CH4) = 0.43 - 0.37Log(Area)	38	0.27	15.0877	0.0004
	Log(Tot-CH4) = 1.01 - 0.77(SecD)	38	0.21	11.1414	0.0019
	Log(Tot-CH4) = 0.42 + 0.55Log(PO ₄ ⁻³)	30	0.22	9.4969	0.0045
	Log(Tot-CH4) = 0.98 - 0.61Log(TN)	32	0.29	13.7928	0.0008
CO ₂					
Direct Ebullition (summer)	Log(ES-CO2) = -1.72 - 0.50Log(Area)	32	0.30	14.6253	0.0006
Direct Ebullition (winter)	Log(EW-CO2) = -2.78 - 0.76Log(Area)	30	0.63	52.0960	0.0000
	Log(EW-CO2) = -1.83 - 0.76Log(TN)	26	0.24	9.0882	0.0058

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Table 5. Mann–Whitney and Kruskal–Wallis test results of the limnological and geographical characteristics of lakes using mode of dissolved gases concentrations (CH₄, O₂) during winter and summer. (≠) indicates a significant difference between a geographic characteristic and flux when $Z > 1.96$; (=) indicates no significant difference. Latitude: I – interior, N – northern, S – southern according to Sect. 2.1; Permafrost Soil Type (Y – yedoma/NY – non-yedoma); Trophic State Index (TSI), Ecozonal Categories (EC), Deposit type (DN) according to descriptions in Table 1; Maximum depth known (MD) and Area (A). In the MD analysis we considered two categories: shallow lakes ≤ 2.5 m and deeper lakes > 2.5 m. In the A analysis we considered two categories: small lakes ≤ 0.1 km² and large lakes > 0.1 km².

Dissolved Gas (Season)	Latitude	Y/NY	TS	EC	DN	MD	A
CH ₄ (Winter)	I ≠ S	≠	D ≠ O	=	E ≠ GL, GMD	≠	≠
CH ₄ (Summer)	I ≠ N, S	≠	D ≠ O, UO	NBF ≠ ArT, SBF, FoT	E ≠ GMD	=	≠
O ₂ (Winter)	I ≠ S	≠	D ≠ O	=	E ≠ GL, GMD	=	≠
O ₂ (Summer)	I ≠ N, S	≠	D ≠ O, UO	NBF ≠ ArT, SBF, FoT	E ≠ GL, GMD	=	≠

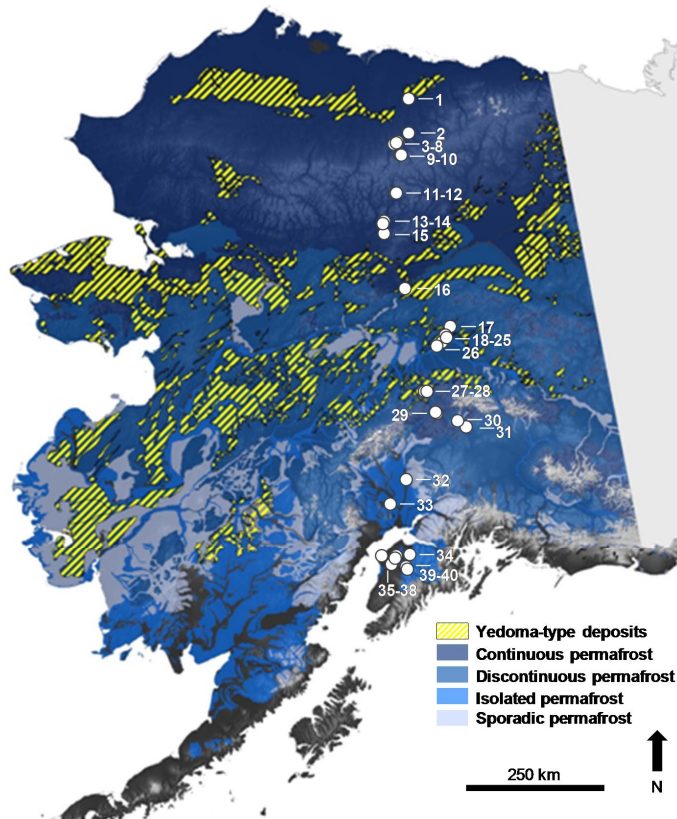


Figure 1. Locations of study lakes in Alaska (circles) plotted on the Alaska DEM hillshade raster. Information about the distribution of yedoma-type deposits (ice-rich silt containing deep thermokarst lakes) and permafrost was from Jorgenson et al. (2008) and Kanevskiy et al. (2011). The Alaska map is the National Elevation Data Set 30 m hillshade raster.

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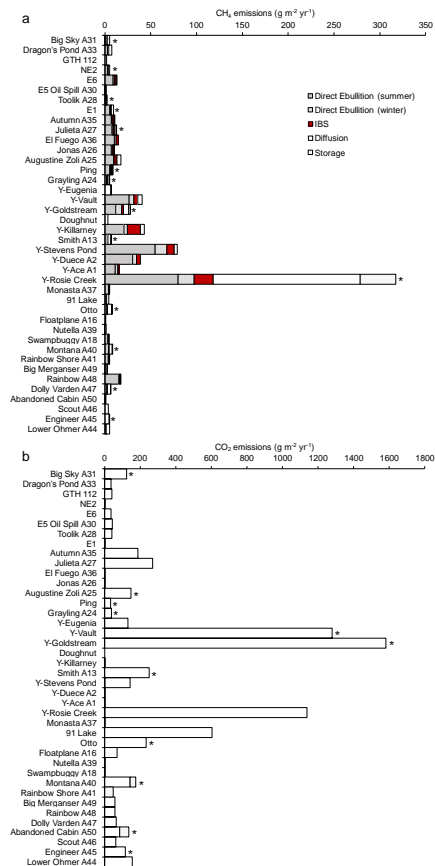


Figure 2. Total annual CH₄ (a) and CO₂ (b) emissions by mode from 40 lakes along a north-south latitudinal transect in Alaska. Yedoma lakes are indicated by “Y”. Lakes for which all emission modes were measured are indicated by “*” (see Table 2). Panels (a) and (b) follow the legend shown in (a).

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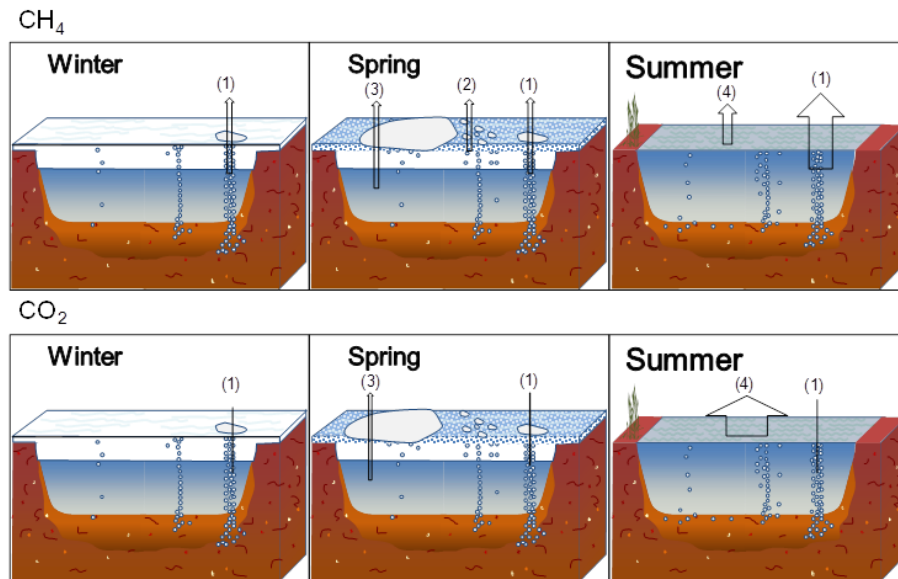


Figure 4. Illustration of CH₄ and CO₂ emissions pathways during different seasons in Alaskan lakes. The thickness of arrows indicates the relative magnitude of contribution from each pathway according to Table 2: (1) Direct Ebullition through ice-free Hotspot seeps in winter and from all seep classes during the last month of ice cover in spring and in summer; (2) Ice-Bubble Storage (IBS) emission during spring ice melt; (3) Storage emission of dissolved gases accumulated under lake ice when ice melts in spring; (4) Diffusion emission from open water in summer.

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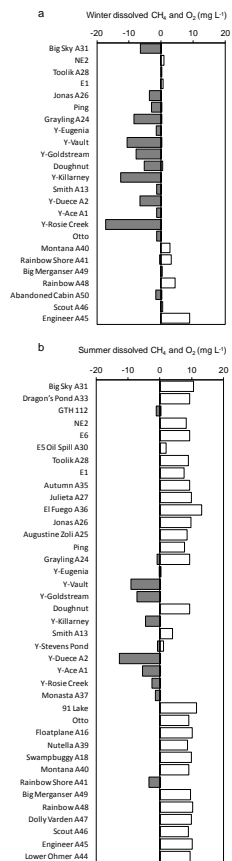


Figure 5. Average dissolved CH₄ (gray bars) and O₂ (white bars) concentrations in lake bottom water during winter (a) and summer (b). Yedoma lakes are indicated by “Y”. In winter, Spearman coefficient $p = 0.58$ indicates a moderate positive correlation between dissolved CH₄ and O₂; in summer $p = 0.70$ indicates a strong positive correlation.

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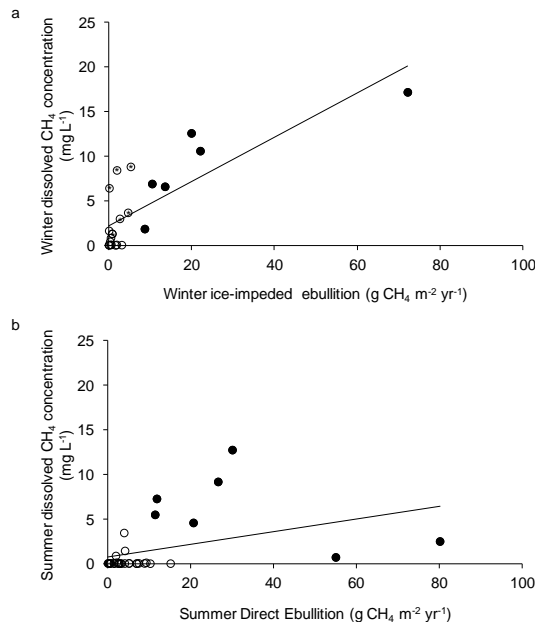


Figure 6. Dissolved CH₄ concentrations measured in lake bottom water vs. winter ice-impeded ebullition in winter (**a**) and Direct Ebullition in summer (**b**). The Spearman coefficients, $\rho = 0.72$ and $\rho = 0.42$ indicate a strong positive correlation and a weak positive correlation in winter and summer, respectively. All lakes were considered a single population; however, yedoma lakes (closed circles) had higher concentrations of lake-bottom dissolved CH₄ (mean \pm SD: 9.3 ± 5.4 mg L⁻¹ winter, 6.7 ± 4.1 mg L⁻¹ summer) and a higher density of ebullition seeps (Sect. 3.2) than non-yedoma lakes (open circles; 2.1 ± 3.0 mg L⁻¹ winter, 0.3 ± 0.7 mg L⁻¹ summer). We observed relatively high concentrations of dissolved CH₄ in some non-yedoma lakes in winter due to dissolved gas exclusion during ice formation in shallow lakes that nearly froze to the lake bed, indicated by *. Excluding lakes that nearly froze to the lake bed, the mean dissolved CH₄ in the remaining non-yedoma lakes was 0.3 ± 0.5 mg L⁻¹ in winter.

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