Geographic and seasonal variation of dissolved methane and aerobic methane oxidation in Alaskan lakes

K. Martinez-Cruz[1,2], A. Sepulveda-Jauregui[2], K. Walter Anthony[2] and F. Thalasso[1,2]

[1] {Biotechnology and Bioengineering Department, Cinvestav, 07360 Mexico City, D.F., Mexico}

[2] {Water and Environmental Research Center, University of Alaska Fairbanks, P. O. Box 5860, 99775 Fairbanks, Alaska, USA}

Correspondence to: F. Thalasso, (thalasso@cinvestav.mx)

Abstract

Methanotrophic bacteria play an important role oxidizing a significant fraction of methane (CH_4) produced in lakes. Aerobic CH_4 oxidation depends mainly on lake CH_4 and oxygen (O_2) concentrations, in such manner that higher MO rates are usually found at the oxic/anoxic interface, where both molecules are present. MO also depends on temperature, and via methanogenesis, on organic carbon input to lakes, including from thawing permafrost in thermokarst (thaw)-affected lakes.

Given the large variability in these environmental factors, CH_4 oxidation is expected to be subject to large seasonal and geographic variations, which have been scarcely reported in the literature. In the present study, we measured CH_4 oxidation rates in 30 Alaskan lakes along a north-south latitudinal transect during winter and summer with a new field laser spectroscopy method. Additionally, we measured dissolved CH_4 and O_2 concentrations. We found that in the winter, aerobic CH_4 oxidation was mainly controlled by the dissolved O_2 concentration, while in the summer it was controlled primarily by the CH_4 concentration, which was scarce compared to dissolved O_2. The permafrost environment of the lakes was identified as another key factor. Thermokarst (thaw) lakes formed in yedoma-type permafrost had significantly higher CH_4 oxidation rates compared to other thermokarst and non-thermokarst lakes formed in non-yedoma permafrost environments. As thermokarst lakes formed in yedoma-type

permafrost have been identified to receive large quantities of terrestrial organic carbon from thaw and subsidence of the surrounding landscape into the lake, confirming the strong coupling between terrestrial and aquatic habitats and its influence on CH_4 cycling.

1 Introduction

Northern lakes are an important source of atmospheric CH_4 (Bastviken et al. 2011), and it has been estimated that they are responsible for as much as 6% of global emission to the atmosphere (Walter et al., 2007). Methane emission from aquatic ecosystems is significantly mitigated by CH_4 oxidation (MO) by aerobic methanotrophs, a group of gram-negative bacteria that use CH_4 as a carbon and energy source (Murrell et al., 1993; Trotsenko and Murrell, 2008). It has been estimated that globally, 30 to 99% of total CH_4 produced in freshwater ecosystems is microbiologically oxidized in the water column rather than being released to the atmosphere (Bastviken et al., 2002; Thauer et al., 2008). Likewise, MO plays an important role in northern lakes specifically by oxidizing up to 88% of the CH_4 diffusing through the water column (Kankaala et al., 2006, 2007; Bellido et al., 2011). As recently demonstrated using stable isotopes, after assimilating CH_4, methanotrophs are incorporated into the lake food web by zooplankton (Kankaala et al., 2006; Jones and Grey, 2011), *Daphnia magna* (Taipale et al., 2012), *Odonata spp.* (Seifert and Scheu, 2012), and *Chironomus larvae* (Gentzel et al., 2012; Wooller et al., 2012), among others. In addition to CH_4 respiration and conversion to CO_2, MO is therefore a pathway that reincorporates a fraction of the CH_4-C produced into the biogeochemical carbon cycle within lakes.

Several environmental factors directly affect aerobic MO in freshwater ecosystems. First, methanotrophy depends on the availability of both CH_4 and O_2. Higher MO rates are usually found at the oxic/anoxic interface, where both CH_4 and O_2 are present (Utsumi et al., 1998a, 1998b; Bastviken et al., 2002; Liikanen et al., 2002; Carini et al., 2005; Schubert et al., 2010). In turn, CH_4 and O_2 concentrations depend on numerous other processes involved in biogeochemical carbon cycling (Fig. 1). Among these, the most important are methanogenesis producing CH_4, primary production and atmospheric diffusion supplying O_2, and several aerobic metabolic processes that compete with MO for available O_2 (Dzyuban, 2010).

In addition to autochthonous and allochthonous carbon inputs to lakes, permafrost thaw can provide an additional source of labile organic carbon to fuel methanogenesis and carbon mineralization in thermokarst (thaw) lakes (Zimov et al., 1997; Walter et al., 2006). MO in

northern regions is therefore directly and indirectly linked to permafrost type and landscape processes that are highly variable. Permafrost ranges from sporadic to continuous and is also variable in composition (Jorgenson et al., 2008). Yedoma-type permafrost is an organic-rich (about 2% carbon by mass) Pleistocene-age permafrost with ice content of 50–90% by volume (Zimov et al., 2006), which occurs mainly in the previously unglaciated regions of Siberia, Alaska, and NW Canada (Czudek and Demek, 1970; Walter et al., 2007; Kanevskiy et al., 2011; Grosse et al., 2013). Non-yedoma permafrost has a more widespread distribution than yedoma permafrost and is also characterized by a much thinner carbon-rich horizon, variable in composition (Ping et al., 2008; Tarnocai et al., 2009; Hugelius et al. 2014).

Many northern lakes are located in continental climate zones, subject to contrasting seasonal conditions with long, cold winters followed by relatively short, but warm summers. Although psychrotolerant and psychrophilic methanotrophs have been reported (Omelchenko et al., 1993, 1996; Bowman et al., 1997; Trotsenko and Khmelenina, 2002), MO was reported to occur more efficiently at mesophilic temperature (Semrau et al., 2010). During winter, northern lakes are covered by a thick ice layer for seven to nine months. Surface lake ice impedes oxygen transfer from the atmosphere to the lake and, when snow-covered, substantially reduces light penetration and oxygen production by photosynthesis (White et al., 2008; Clilverd et al., 2009). Thus, the combination of low temperature and limited oxygen availability suggests lower MO rates in northern lakes in winter than in summer.

Given the number of parameters having a potential effect on MO, as well as the patchwork of seasonal and geographic conditions found among northern lakes, MO is expected to exhibit large geographic and seasonal variations that still remain to be characterized. The goal of our study was to determine these variations through measurement of dissolved CH_4 and O_2 as well as MO rates in the winter and summer in 30 lakes along a south-north transect in Alaska.

2   Materials and Methods

2.1   Site description

We sampled 30 Alaskan lakes during two field campaigns, one in late winter (March–April 2011) and one in summer (June–July 2011). To evaluate the effects of latitudinal variation and permafrost type on MO, lakes were selected along a transect from the southcentral Alaskan coast on the Kenai Peninsula to the Arctic Ocean near Prudhoe Bay (Fig. 2). The transect

crossed through glaciated mountain ranges and discontinuous, sporadic, or no permafrost in south-central Alaska; discontinuous to isolated yedoma permafrost in the interior of Alaska; and continuous permafrost in northern Alaska. In this work, for simplicity, lakes located in yedoma-type permafrost areas will be referred to as "yedoma lakes" and all others as "non-yedoma lakes". Geographic variability along the north-south Alaska transect has been previously described for ecosystems, climate, geology, and permafrost type (Gregory-Eaves et al., 2000; Jorgenson et al., 2008; Smith et al., 2010). Additionally, Sepulveda-Jauregui et al. (2015) quantified the surface area of the selected lakes (0.002–1.45 km^2), their trophic states (ultraoligotrophic to eutrophic), and their annual CH_4 fluxes (0.5–317 g CH_4 m^{-2} y^{-1}). Table 1 shows the location and permafrost type of the selected lakes.

2.2 Sampling and field measurements

We sampled lake water usually near the center of each lake. In the winter, the ice cover was drilled through with a motorized auger (0.3 m in diameter). Using a Hydrolab DataSonde (Hach Hydromet, Loveland, CO, USA), we measured temperature, pH, chlorophyll *a*, and dissolved oxygen (DO). The pH and DO sensors of the Hydrolab were calibrated regularly, before and after each section of the latitudinal lake transect (four sections per transect, approximately one calibration per week). Temperature and chlorophyll *a* sensors were not regularly calibrated. All parameters were measured at 0.5 or 1-m depth intervals throughout the water column, except in Dolly Varden L. where measurement intervals were increased to every five meters from 15 m to 25m depth. In lakes shallower than 1 m, we measured Hydrolab parameters at three distributed depths throughout the lake water column.

Water samples for MO rates and dissolved CH_4 concentration were taken at a depth of within 1 m of the ice-water interface in winter and usually at 0.75 to 1 m water depth in summer. Due to differences in lake depth and thickness of the ice sheets, samples reflected surface water in deep lakes, but mid water column or even lake bottom water environment, in shallow lakes. Samples were taken with a horizontal Van Dorn bottle (Wildco, Yulee, FL, USA).

Water density derived from surface and bottom water temperatures were used to determine the relative water column stability (RWCS; Padisak et al., 2003). Lakes with RWCS >56.5 were considered fully stratified, lakes with RWCS <16.3 were considered fully mixed, and lakes with intermediate RWCS were considered partially stratified (Branco et al., 2009). Similarly, we determined whether an oxycline was present in each lake based on a sharp DO gradient or

presence of an oxic/anoxic interface. Detailed temperature and DO profiles are available as a Supplement in Sepulveda-Jauregui et al. (2015). We report all results in mean ± standard deviation (SD).

2.3 Dissolved CH$_4$ concentration and MO rate

To avoid long delays in sample transfer from remote locations to the laboratory, we determined dissolved CH$_4$ concentrations with a previously described method based on Headspace Equilibration using Infrared Tunable Diode Laser Absorption Spectroscopy (HE-TDLAS; Sepulveda-Jauregui et al., 2012). This method consisted of creating a gas/liquid equilibrium in a 100 mL equilibration vial containing 60 mL of lake water sample and 40 mL of headspace (air) by vigorous shaking for 10 s. As previously reported (Sepulveda-Jauregui et al., 2012), this shaking time was enough to reach equilibrium and allowed the non-invasive determination of CH$_4$ concentration in the water sample by measuring headspace concentration with a laser beam crossing the headspace of the equilibration vial, through the glass walls of the vial. This measurement was conducted with a modified open-field CH$_4$ analyzer (GasFinder 2; Boreal Laser, Edmonton, Canada). The CH$_4$ concentration in the water sample was calculated from the measured headspace concentration according to Henry's law. In the present work, all CH$_4$ concentrations are expressed in mg CH$_4$ L^{-1}.

We determined duplicate MO rates in one water sample from each lake taken as described above, using a modified HE-TDLAS method to allow for measurement of MO in the field. This new method was based on a previous development using the HE-TDLAS method for the determination of methanogenic activity (Martinez-Cruz et al., 2012). Two 60-mL lake water subsamples from a single Van Dorn bottle sample were gently transferred to two 100-mL equilibration vials (duplicates). Equilibration vials were immediately closed with rubber stoppers and vigorously shaken for 10 s to transfer most of the dissolved CH$_4$ contained in the water sample to the headspace. Next, the headspace was vented, the vial was closed, and the sample was shaken again to evacuate the residual CH$_4$ content of the water sample. Using this procedure, more than 99.5% of the original CH$_4$ content of the sample was evacuated. The equilibration vials were then closed with rubber stoppers and aluminum crimp caps, spiked with 0.6 mL CH$_4$ (99.0% purity; Air Liquide, Houston, TX, USA) injected with a disposable syringe, and vigorously shaken for 10 s. This approach allowed MO tests to be conducted with an initial standard CH$_4$ concentration in the liquid phase (~0.6 mg L^{-1}). It also provided an initial CH$_4$ to

1   O_2 molar ratio of 0.062, significantly below the stoichiometric ratio (0.5), ensuring no O_2

2   limitation.

3   Equilibration vials were incubated for 10–12 days in a water bath inside insulated boxes placed

4   in our vehicle. In the winter, the vials were maintained at 2 ± 2 °C in a water bath with ice

5   supplements; in the summer, the vials were maintained at 15 ± 2 °C. The temperature of the

6   water bath was measured daily. We measured the CH_4 concentration in the equilibration vials

7   daily using the HE-TDLAS method described in detail by Sepulveda-Jauregui et al. (2012).

8   Briefly, dry control MO test vials containing only CH_4 standards were read by the TDLAS for

9   calibration. Each experimental equilibration vial was vigorously shaken for 10 s to reach phase

10   equilibrium and then immediately placed in the laser beam path, after which a stable HE-

11   TDLAS reading was typically observed within 5 s. Five readings were taken for each MO test

12   vial and recalibration was conducted after measuring each set of test vials to ensure instrument

13   stability. The field HE-TDLAS method allowed measurement of dissolved CH_4 and MO rates.

14   This technique was simple, rapid (about 60 s per sample measurement), non-invasive, and

15   avoided complications and long delays in sample transfer from remote locations to the

16   laboratory.

17   We calculated the total CH_4 concentration (C_{CH4} = total CH_4 mass present in the gas and liquid

18   phases divided by the sample liquid volume) in each vial during the MO tests. MO rates were

19   determined from the decrease in C_{CH4} in the equilibration vials with time. MO rates determined

20   by this method represent the MO rate after aeration and CH_4 addition (vials spiked with CH_4

21   and vigorously shaken). Thus, these MO rates do not correspond to actual observations of in

22   situ DO and dissolved CH_4 concentrations in the lakes. The measured CH_4 oxidation rate was

23   considered the potential MO (r_{max}; mg CH_4 L^{-1} d^{-1}) under non-limiting CH_4 and DO

24   concentrations. To estimate the actual rate (r; mg CH_4 L^{-1} d^{-1}) from r_{max}, a double Monod model

25   was used (Bae and Rittmann, 1996; Segers, 1998) in which C_{CH4} and C_{O2} represent the actual

26   dissolved CH_4 and DO concentrations measured in the lake, respectively, and K_{S-CH4} and K_{S-O2}

27   are the apparent affinity constants of the methanotrophic community, for CH_4 and DO,

28   respectively:

29   $$r = r_{max} \cdot \frac{C_{CH4}}{K_{S-CH4} + C_{CH4}} \cdot \frac{C_{O2}}{K_{S-O2} + C_{O2}} \qquad (1)$$

30   Average K_{S-CH4} and K_{S-O2} values for lakes have been determined by previous studies: $K_{S-CH4} =$

31   0.110 ± 0.053 mg L^{-1} (mean $\pm$ SD; Liikanen et al., 2002; Lofton et al., 2013) and $K_{S-O2} = 0.624$

1 $\pm$ 0.064 mg L^{-1} (mean $\pm$ SD; Lidstrom and Somers, 1984; Frenzel et al., 1990). To the best of

2 our knowledge, the highest K$_{S\text{-}CH4}$ reported in lakes is 0.704 mg L^{-1} (Liikanen et al., 2002). It

3 should be noted that these reported K$_S$ values refer to the apparent affinity constants for the

4 methanotrophic community, rather than the half-saturation constant for the CH$_4$

5 monooxygenase enzyme that catalyzes CH$_4$ oxidation. The potential error caused by using

6 previously reported K$_S$, instead of experimentally determined values will be considered in the

7 discussion section.

8 To establish the extent of potential MO limitation by CH$_4$ or DO, two limitation factors were

9 defined, where β is the limitation factor for CH$_4$ (%) and γ is the limitation factor for DO (%):

10 $$0\% \leq \beta = \left(1 - \frac{C_{CH4}}{K_{S-CH4} + C_{CH4}}\right) \cdot 100 \leq 100\% \qquad (2)$$

11 $$0\% \leq \gamma = \left(1 - \frac{C_{O2}}{K_{S-O2} + C_{O2}}\right) \cdot 100 \leq 100\% \qquad (3)$$

12 A limitation factor of 100% means that 100% of a process ceases to occur due to the absence

13 of the limiting substrate, while a limitation factor of 0% indicates a process occurring at

14 maximum rate ($r = r_{max}$). When $\beta > \gamma$, CH$_4$ was considered to be the limiting factor; conversely,

15 when $\gamma > \beta$, DO was considered to be the limiting factor.

2.4 Statistical analyses

17 Normality was assessed by the Shapiro-Wilk test. Since most of the data was non-normally

18 distributed and with unequal samples number, significant differences among all parameters

19 were determined using Kruskal-Wallis multiple comparison test (differences were considered

20 significant at $p < 0.05$, Z > 1.96). To assess whether CH$_4$ was oxidized during the MO

21 incubation tests, significant differences between C_{CH4} were determined by an analysis of

22 variance (ANOVA; $p < 0.05$), after normality was assessed by the Shapiro-Wilk test. Statistical

23 analyses were conducted using the NCSS 2000 Statistical Analysis System software (Number

24 Cruncher Statistical Systems, Kaysville, UT, USA). Linear regressions were also conducted to

25 determinate the MO rates using Wolfram Mathematica 7.0 (Wolfram, Minneapolis, MN, USA).

26

3 Results

3.1 Physicochemical parameters

The sampled lakes were shallow; other than four atypical lakes with a maximum known depth >20 m (lakes #4, #24, #26 and #30), the average lake depth in summer was 4.5 ± 2.6 m (mean ± SD). During winter, none of the lakes was completely frozen at the sampling stations. Liquid water was always present underneath the ice cover, which ranged in thickness from 0.60 to 1.25 m (mean ± SD, 0.81 ± 0.14 m). The mean temperature, measured at all depth throughout the lake water columns with the Hydrolab probe was 2.4 ± 0.6 °C (mean ± SD, n = 103) in the winter and 13.9 ± 2.4 °C (mean ± SD, n = 235) in the summer. According to RWCS, during the summer, 15 lakes of the 28 for which a complete temperature profile was determined were fully thermally stratified. Six lakes were partially stratified and seven lakes were mixed. During the winter, 16 of 18 lakes for which a complete temperature profile was determined were fully mixed, while two lakes were partially stratified and none was fully stratified. We observed temperature inversion in 15 of the 18 lakes, with temperature gradients ranging from -0.1 to -3.4 °C, with an average of -1.4 °C (top minus bottom temperature). Overall, only one third of the temperature profiles indicated clear stratification. In both seasons, no correlation between RWCS and lake depth was found, probably due to the fact that lakes were shallow and with an uneven depth distribution.

Lake water pH ranged from 5.9 to 8.2 in winter and 6.3 to 9.2 in summer among the study lakes. Chlorophyll *a* was only detected during the summer, ranging from 1.0 to 45.9 µg L^{-1} (manufacturer detection limit, 0.03 µg L^{-1}). The concentration of dissolved CH_4 in the 30 lakes ranged from 0.01 to 14.77 mg L^{-1} during the winter and from 0.02 to 1.51 mg L^{-1} during the summer (Table 2). The DO concentration at the same depths ranged from 0.10 to 13.63 mg L^{-1} during the winter and from 0.22 to 11.07 mg L^{-1} during the summer (Table 2). During summer, a clear oxycline was observed in all yedoma lakes, but only in six of 20 non-yedoma lakes. In contrast, during winter, an oxycline was not observed in any of the yedoma lakes, which were largely anaerobic throughout the whole water column. We observed an oxycline in winter in four of 13 non-yedoma lakes. Overall, an oxycline was observed in 30% of the DO profiles. Temperature-oxygen profiles for all 30 studied lakes are shown in Sepulveda-Jauregui et al. (2015).

1   Fig. 3 shows the statistical distributions of the dissolved CH_4 and DO concentrations, as well

2   as the Kruskal-Wallis comparisons. Significant differences were observed between yedoma and

3   non-yedoma lakes ($p < 0.05$). In yedoma lakes, the CH_4 and DO concentrations were

4   significantly higher and lower, respectively, than in non-yedoma lakes during both seasons

5   (Kruskal-Wallis test, $p < 0.05$). In addition to differences related to permafrost type, higher

6   CH_4 concentrations and lower DO concentrations were observed during the winter than in the

7   summer (Fig. 3) and an apparent geographic trend was observed. Higher dissolved CH_4 and

8   lower DO concentrations were found in lakes from central Alaska than in those from southern

9   and northern Alaska (Sepulveda-Jauregui et al., 2015).

10   **3.2 Methane oxidation rates**

11   The HE-TDLAS method allowed us to determine the MO potential in the field in all studied

12   lakes. Fig. 4 shows three representative C_{CH4} trends observed in the MO vials. In some cases,

13   MO began on the first day of incubation (Fig. 4a) and the initial slope of the change in C_{CH4}

14   was taken into account in determining the MO rate. In about 60% of the cases during the

15   summer and 80% during the winter, a lag phase was observed; i.e. period of time with no

16   apparent MO (Fig. 4b). This behavior, termed "induction of MO", has previously been reported

17   for various soils (Bender and Conrad, 1995; Dunfield et al., 1999) and can be interpreted as an

18   adaptation period of the CH_4 oxidizers to the culture conditions. In lakes in which this pattern

19   was observed, the lag phase was not taken into account and the MO rate was instead determined

20   from the slope of C_{CH4} after the lag phase. When no significant decrease in C_{CH4} was observed

21   during the first seven days (Fig. 4c; ANOVA , $p < 0.05$), we assumed an MO rate of zero,

22   consistent with previous reports for various soils (Whalen et al., 1990; Bender and Conrad,

23   1995; Dunfield et al., 1999). We observed MO rates of zero in only three non-yedoma lakes

24   during winter. Otherwise, no correlation with lake morphology, season, or permafrost type was

25   observed in regard to the existence of a lag phase or its duration.

26   The potential MO rate r_{max} ranged from 0.000 to 0.488 mg L^{-1} d^{-1} during the winter and from

27   0.073 to 1.339 mg L^{-1} d^{-1} during the summer (Fig. 5a). Seasonal variation of r_{max} was significant,

28   with summer r_{max} up to 47 times higher than winter rates. Permafrost type was also an important

29   determining factor, because during the summer, yedoma lakes had higher r_{max} than non-yedoma

30   lakes (Kruskal-Wallis test, $p < 0.05$); specifically, r_{max} was 0.71 ± 0.36 and 0.29 ± 0.16 mg L^{-1}

31   d^{-1} (mean $\pm$ SD) for yedoma and non-yedoma lakes, respectively. However, during the winter,

32   no significant differences were observed between yedoma and non-yedoma lakes. In addition

1 to differences related to permafrost type, an apparent latitudinal pattern was also observed, with

2 higher r_{max} for lakes from central Alaska compared to those from southern and northern Alaska

3 (Fig. 5a).

4

4 Discussion

4.1 Geographic and seasonal variations in physicochemical parameters

7 In yedoma lakes, the CH_4 and DO concentrations were significantly higher and lower,

8 respectively, than in non-yedoma lakes during both seasons. This observation is most likely due

9 to higher organic carbon and nutrient inputs associated with thawing permafrost in yedoma-

10 type lakes. Walter Anthony et al. (2014) and Sepulveda-Jauregui et al. (2015) showed that

11 thawing yedoma permafrost not only provides ancient (Pleistocene-aged) organic carbon

12 stimulating CH_4 production but also phosphate and nitrogen (ammonium), which promotes

13 bacterial, algal and contemporary plant growth in and around lakes. Since terrestrial plant

14 matter surrounding lakes gets deposited in thermokarst-lake sediments as lakes laterally

15 expand, both enhanced allochthonous and autochthonous productivity of yedoma-type lake

16 ecosystems results in higher rates of contemporary organic matter loading to sediments of

17 yedoma-type lakes compared to non-yedoma lakes (Walter Anthony et al., 2014).

18 Contemporary organic matter decomposes in part to form CH_4 in surface lake sediments. In

19 contrast, ancient yedoma carbon is decomposed throughout the sediment profile (Fig. 1), with

20 particularly high rates of methanogenesis occurring along the permafrost thaw front, located

21 deep in the thaw bulb beneath the lake (Heslop et al., 2015). Methane produced at depth in the

22 thaw bulb subsequently migrates, primarily as free-phase bubbles through bubble tubes in

23 sediments, to the surface sediments where it escapes the lake via ebullition (Walter Anthony

24 and Anthony 2013; Tan et al. 2015). Thus higher organic carbon and nutrient inputs in yedoma-

25 type lakes promote higher anaerobic metabolism in the sediments together with aerobic

26 metabolism in the water column, leading to higher CH_4 and lower DO concentrations in the

27 water column.

28 In both yedoma and non-yedoma lakes, higher CH_4 concentrations and lower DO

29 concentrations were observed during the winter than in the summer (Fig. 3). This seasonal

30 variation can be attributed to thick ice covering the lakes in winter. Ice cover impedes gas

31 exchange between the water and the atmosphere, promoting CH_4 build-up in the water column

(Phelps et al., 1998; Bastviken et al., 2004; Juutinen et al., 2009) and hindering O_2 transfer from the atmosphere, except in some locations where high-flux ebullition seeps allow gas exchange through local holes in lake ice (Greene et al., 2014). Ice and snow also reduce light penetration and oxygen production by photosynthesis beneath the ice (White et al., 2008; Clilverd et al., 2009). The absence of detectable levels of chlorophyll *a* in ice-covered lakes during March and April (see results section) despite the longer springtime photoperiod was supportive evidence of reduced photosynthesis under the ice. In summer, although CH_4 production was probably higher due to warmer sediments, it did not cumulate in the water column and was released to the atmosphere (Fig. 1).

Geographic variations were also observed with higher dissolved CH_4 and lower DO concentrations being found in lakes from central Alaska than in those from southern and northern Alaska. However, this apparent latitudinal pattern was related to the higher proportion of yedoma lakes in central Alaska. No significant latitudinal trend was observed when yedoma and non-yedoma lakes were analyzed separately (Kruskal-Wallis test, $p < 0.05$).

Fig. 3 shows that when relatively high CH_4 concentrations were found, relatively low DO concentrations were observed and conversely. This pattern was particularly clear in yedoma lakes: in winter, a CH_4 concentration of 7.32 ± 5.86 mg L^{-1} (mean $\pm$ SD) was found, while the DO concentration was 0.13 ± 0.03 mg L^{-1} (mean $\pm$ SD). In the same yedoma lakes, the summer CH_4 concentration was 0.49 ± 0.52 mg L^{-1} (mean $\pm$ SD), while the DO concentration was 3.19 ± 3.24 mg L^{-1} (mean $\pm$ SD). This observation suggests that MO was a significant contributor of the biogeochemical processes, actively controlling O_2 and CH_4 concentrations by oxidizing CH_4 when O_2 was present. To confirm the latter, it would be necessary to measure experimentally the O_2 uptake rate by methanotrophs and by other aerobic processes that compete with MO (Dzyuban, 2010).

The trend toward higher CH_4 concentrations and lower DO concentrations in winter than in summer was not as strong in non-yedoma lakes as in yedoma lakes (Fig. 4). These results provide additional evidence that in non-yedoma lakes, the lower organic carbon inputs fuels more weakly methanogenesis and aerobic processes including MO than in yedoma lakes, resulting in a lower seasonal variation of CH_4 and DO concentration. Another reason is that yedoma lakes have a significantly higher ebullition year round (Walter et al., 2007; Sepulveda-Jauregui et al., 2015). Even during winter, Greene et al. (2014) found that 80% of CH_4 in

1 ebullition bubbles trapped under the ice cover dissolves into the lake water column before being

2 confined within the growing ice sheet, leading to elevated dissolved CH_4 beneath the ice.

4.2   Limiting factors of MO rates

4 The actual MO rates r ranged from 0.000 to 0.124 mg L^{-1} d^{-1} during the winter and from 0.017

5 to 0.538 mg L^{-1} d^{-1} during the summer (Fig 6b), which as expected were significantly lower

6 than the potential MO rates. These r values are within the range reported for arctic lakes, which

7 ranges over 3 magnitude order, from 0.001 to 1 mg L^{-1} d^{-1} (Liikanen et al., 2002; Kankaala et

8 al., 2006; Lofton et al., 2014). Similarly, r values were 1 to 50-fold higher in the summer than

9 in the winter. We attribute this finding to the temperature dependence of methanotrophy

10 (Semrau et al., 2008; Borrel et al., 2011), but also to the limited DO concentration under the ice

11 cover during the winter.

12 In addition to seasonal variations, permafrost type was also a determining factor of r and r_{max}.

13 As mentioned before, although no difference in r_{max} was observed during winter between

14 yedoma and non-yedoma lakes, r_{max} in yedoma lakes was about twice higher than in non-

15 yedoma lakes during summer. We attribute that difference to a more active MO methanotrophic

16 community in yedoma lakes, as all r_{max} tests were conducted in aerated vials with an initial

17 standard CH_4 concentration in the liquid phase (~0.6 mg L^{-1}), thus ensuring similar and non-

18 limiting conditions. As observed with r_{max}, during summer yedoma lakes showed 2–3 times

19 higher r than non-yedoma lakes (Kruskal-Wallis test, $p < 0.05$; $r = 0.28 \pm 0.17$, mean $\pm$ SD,

20 yedoma lakes; $r = 0.09 \pm 0.08$ mg L^{-1} d^{-1}, mean $\pm$ SD, non-yedoma lakes). Higher r values for

21 yedoma lakes in summer is explained by the higher dissolved CH_4 concentration in presence of

22 a relatively high DO concentration above the oxycline (Fig. 3). As observed with CH_4 and DO

23 concentrations, no significant latitudinal trend in MO was observed, when yedoma and non-

24 yedoma lakes were analyzed separately.

25 The actual MO rates; r, were determined from r_{max} and CH_4 and DO concentrations using two

26 affinity constants, K_{S-CH4} and K_{S-O2}. These affinity constants are highly variable, because their

27 determination is challenging and subject to relatively high determination error (Segers et al.,

28 1998) and because the methanotrophic community is sensitive to numerous factors and changes

29 over time and space (Carini et al., 2005; He et al., 2012). For instance, Lofton et al. (2014)

30 reported a variation of 150% in K_{S-CH4} within the hypolimnetic water column of two lakes with

31 similar characteristics. The determination of MO rates may, therefore, be subject to large error

if reported values are used instead of experimental parameters or because of standard error associated to experimental K_S determination (Kovarova-Kovar and Egli, 1998). To quantify these potential errors, a sensitivity analysis was conducted. We arbitrarily modified K_{S-CH4} and K_{S-O2} and calculated the resulting r (Eq. 1) using the experimental r_{max}, C_{CH4}, and C_{O2} measured in the 30 lakes. Fig. 6 shows the error on r caused by a given error on K_{S-O2} (Fig. 6a) and K_{S-CH4} (Fig. 6b), for yedoma and non-yedoma lakes, in winter and in summer. According to this analysis, an underestimation of K_{S-O2} or K_{S-CH4} would lead to an overestimation of the actual MO rate (positive error), while an overestimation of these affinity constants would produce an underestimation of r (negative error). Fig. 6a shows that, an error on K_{S-O2} ranging from -50% to 200%, would cause from 10% to -6% error on r, for all lakes and all seasons, except in yedoma lakes during winter, where an error from 75% to -50% would be generated. This relatively high sensitivity of r to error in K_{S-O2} in yedoma lakes during winter is due to DO concentrations close to K_{S-O2}. Likewise, Fig. 6b shows that, from an error on K_{S-CH4} ranging from -50% to 200%, a resulting error on r from 6% to -4% would be done, for all lakes and all seasons, except in non-yedoma lakes during summer, where an error from 50% to -34% would be generated. As above, the latter is due to CH_4 concentrations close to K_{S-CH4} in non-yedoma lakes during summer. This sensitivity analysis shows that, other than for K_{S-O2} in yedoma lakes during winter and K_{S-CH4} in non-yedoma lakes during summer, errors on K_S would have relatively little impact on determination of methanotrophic rates. The potentially significant error on methanotrophic rates in yedoma lakes during winter and in non-yedoma lakes during summer encourages further studies including experimental K_S determination.

From Eq. 2 and 3, we estimated that, during the summer CH_4 was the main limiting factor in 25 out of 30 lakes. In contrast, during winter, CH_4 was the main limiting factor in 10 of 26 lakes (Table 2). Notably, during the winter, DO was the limiting factor of MO for all seven yedoma lakes, while during the summer, CH_4 was the limiting factor for all non-yedoma lakes. A similar error analysis was done on β and γ, as done with r, to estimate if the estimated limiting factor would change as a result of error on K_S ranging from -50% to 200%. The results showed no impact on the limiting factor in the 30 lakes and for both seasons. These results confirm that MO was mainly controlled by DO and CH_4 availability, which in turn, depended on the season and landscape processes.

A potential bias in our r estimates may have arisen from taking water samples at a single depth in each lake. The literature has clearly shown that a higher MO rate is often found at the

oxic/anoxic interface in stratified lakes (Utsumi et al., 1998a, 1998b; Bastviken et al. 2002; Carini et al., 2005; Pimenov et al., 2010; Schubert et al., 2010). Estimation of MO rates consistently measured at a single depth that was not necessarily located at the oxic/anoxic interface may have neglected potentially higher rates occurring at the oxic/anoxic interface in stratified lakes. However, in the present study, the sampled lakes were in many cases shallow, relatively well mixed, and without a clear oxycline (see Results section), suggesting a relatively homogeneous water column. Utsumi et al. (1998b) observed homogeneous MO rates at all depths of a shallow and mixed temperate lake, while Rudd and Hamilton (1978) also reported homogeneous MO rates during overturn of a dimictic lake. Determination of MO rates at the oxic/anoxic interface, in the few cases in which such an interface was observed, would likely have indicated higher MO rates. Thus, the results of r presented here, may be underestimated to an unknown extent.

5   Conclusions

We developed a new method based on a TDLAS for the determination of MO rates together with dissolved CH_4 concentration in lakes in the field. This method was successfully applied to 30 lakes along a north-south transect and allowed for the determination of MO potentials ranging from 0.000 to 1.339 mg L^{-1} d^{-1} in winter and summer. MO rates in water of Alaskan lakes showed high seasonal and geographic variability. In addition to temperature effects, the main factors controlling MO were: 1) CH_4 availability during the summer, limited both by exchange with the atmosphere and by MO itself; 2) DO availability during the winter, mainly due to ice cover impeding gas exchange with the atmosphere and primary production; and 3) inputs of organic substrates to lakes, mainly related to the presence or absence of yedoma permafrost as an additional source of carbon and nutrients. These results indicate that MO may substantially mitigate the increase in CH_4 emission predicted by permafrost thawing (Khvorostyanov, et al. 2008; Walter Anthony et al., 2014).

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1   **Tables**

2

3   **Table 1.** Identification, location, and permafrost soil type for lakes included in the study.
4   *Indicates informal lake name, yedoma lakes are marked on light grey.

#	Name	Lat.	Long.	Permafrost type
1	Big Sky* A31	69.581	-148.639	Non-yedoma
2	GTH 112	68.672	-149.249	Non-yedoma
3	NE2	68.647	-149.582	Non-yedoma
4	Toolik A28	68.632	-149.605	Non-yedoma
5	E1	68.626	-149.555	Non-yedoma
6	Julieta* A27	68.447	-149.369	Non-yedoma
7	El Fuego* A36	67.666	-149.716	Non-yedoma
8	Jonas* A26	67.647	-149.722	Non-yedoma
9	Augustine Zoli* A25	67.138	-150.349	Non-yedoma
10	Ping*	67.136	-150.370	Non-yedoma
11	Grayling* A24	66.954	-150.393	Non-yedoma
12	Eugenia*	65.834	-149.631	Yedoma
13	Goldstream*	64.916	-147.847	Yedoma
14	Killarney*	64.870	-147.901	Yedoma
15	Smith A13	64.865	-147.868	Non-yedoma
16	Stevens Pond*	64.863	-147.871	Yedoma
17	Duece A2	64.863	-147.942	Yedoma
18	Ace A1	64.862	-147.937	Yedoma
19	Rosie Creek*	64.770	-148.079	Yedoma
20	Otto	63.842	-149.037	Non-yedoma
21	Floatplane* A16	63.394	-148.670	Non-yedoma
22	Montana A40	62.143	-150.048	Non-yedoma
23	Rainbow Shore* A41	61.694	-150.089	Non-yedoma
24	Big Merganser A49	60.726	-150.644	Non-yedoma
25	Rainbow A48	60.719	-150.808	Non-yedoma
26	Dolly Varden A47	60.704	-150.787	Non-yedoma
27	Abandoned Cabin* A50	60.696	-151.315	Non-yedoma
28	Scout A46	60.533	-150.843	Non-yedoma
29	Engineer A45	60.478	-150.323	Non-yedoma
30	Lower Ohmer A44	60.456	-150.317	Non-yedoma

5

1 **Table 2.** Methane oxidation parameters for 30 Alaskan lakes. * indicates median; ND - Not

2 determined; BDL - Bellow detection limit, yedoma lakes are marked on light grey.

#	CH_4 (mg L^{-1})		O_2 (mg L^{-1})		Potential MO (mg L^{-1} d^{-1})		Actual MO (mg L^{-1} d^{-1})		Limiting factor	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
1	6.43	0.05	0.13	10.53	0.23	0.11	0.08	0.03	O_2	CH_4
2	0.58	0.09	0.43	8.28	0.14	0.36	0.05	0.15	O_2	CH_4
3	0.02	0.05	1.73	9.80	0.12	0.07	0.02	0.02	CH_4	CH_4
4	0.11	0.03	10.09	9.46	BDL	0.28	0.00	0.06	CH_4	CH_4
5	0.05	0.04	9.59	9.52	0.10	0.19	0.03	0.05	CH_4	CH_4
6	0.08	0.07	ND	9.81	0.12	0.20	ND	0.09	ND	CH_4
7	ND	0.06	ND	9.65	ND	0.18	ND	0.04	ND	CH_4
8	3.68	0.03	13.63	10.30	0.03	0.18	0.03	0.04	O_2	CH_4
9	8.83	0.11	3.64	9.87	0.05	0.39	0.04	0.19	O_2	CH_4
10	3.00	0.06	0.25	6.94	0.11	0.11	0.03	0.03	O_2	CH_4
11	8.43	0.88	0.19	9.31	BDL	0.28	0.00	0.23	O_2	CH_4
12	0.79	0.07	0.15	6.90	0.09	0.29	0.02	0.11	O_2	CH_4
13	8.43	0.19	0.11	6.23	0.49	0.54	0.07	0.48	O_2	O_2
14	12.59	0.31	0.09	0.31	0.20	0.92	0.03	0.30	O_2	O_2
15	1.30	0.02	0.23	3.93	0.05	0.31	0.01	0.05	O_2	CH_4
16	ND	0.72	0.11	1.36	ND	0.34	ND	0.20	ND	O_2
17	6.60	0.59	0.19	0.57	0.06	1.34	0.01	0.54	O_2	O_2
18	0.70	0.03	0.14	6.74	0.02	0.77	0.00	0.15	O_2	CH_4
19	14.77	1.51	0.13	0.22	0.20	0.74	0.04	0.19	O_2	O_2
20	1.24	0.03	0.31	9.47	0.05	0.67	0.01	0.15	O_2	CH_4
21	ND	0.04	ND	9.52	ND	0.33	ND	0.08	ND	CH_4
22	0.08	0.05	2.79	11.07	0.05	0.20	0.01	0.06	CH_4	CH_4
23	0.30	0.08	5.84	9.59	0.02	0.68	0.01	0.33	CH_4	CH_4
24	0.04	0.02	12.40	9.66	0.06	0.34	0.02	0.08	CH_4	CH_4
25	0.08	0.03	11.91	10.20	0.32	0.25	0.12	0.04	CH_4	CH_4
26	0.01	0.03	10.00	10.24	0.04	0.08	0.00	0.02	CH_4	CH_4
27	0.03	0.02	7.90	9.67	0.15	0.41	0.03	0.07	CH_4	CH_4
28	0.07	0.04	0.20	9.01	BDL	0.38	0.00	0.09	O_2	CH_4
29	0.04	0.04	9.13	10.19	0.02	0.28	0.00	0.05	CH_4	CH_4
30	ND	0.03	ND	10.25	ND	0.38	ND	0.11	ND	CH_4
Mean										
Global	3.29	0.47	3.91	7.95	0.10	0.39	0.03	0.13	O_2^*	CH_4^*
Yedoma	7.53	1.73	0.14	3.19	0.18	0.71	0.03	0.28	O_2^*	CH_4^*
Non-yedoma	2.02	0.09	5.30	9.40	0.08	0.29	0.03	0.09	CH_4^*	CH_4^*

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Figure captions

Figure 1. Carbon cycling in northern high-latitude lakes during the summer and winter. Carbon (C_{org}) release from primary production and landscape processes promotes CH_4 production and competes with MO for O_2.

Figure 2. Locations of studied Alaskan lakes (white circles) plotted on the Alaska DEM hillshade raster. Information about the distribution of yedoma-type deposits (Pleistocene-aged, ice-rich silt containing deep thermokarst lakes) was from Jorgenson et al. (2008) and Kanevskiy et al. (2011). The Alaska map is the National Elevation Data Set 30 m hillshade raster.

Figure 3. Statistical distributions of CH_4 (white boxes) and DO (grey boxes) water concentrations in yedoma and non-yedoma lakes during the winter and summer. The boxes include the median (Q2) and the quartile range (Q1 and Q3). The whiskers show minimum and maximum data. The open circles show outlier data. Capital letters are Kruskal-Wallis multiple comparison test; values with the same capital letter are not significantly different ($p < 0.05$, Z > 1.96). *n* represents the number of lakes measured.

Figure 4. Examples of CH_4 oxidation patterns observed during the MO assays: (a) assay with no lag-phase. (b) assay with a 3-day lag-phase. and (c) assay with no detected activity. Straight lines are linear correlations.

Figure 5. (a) CH_4 oxidation potential (r_{max}) and (b) CH_4 oxidation rates observed in 30 lakes along a north-south transect (left-right) in Alaska during the summer (white bars) and the winter (black bars).

Figure 6. Sensitivity analysis of the impact of an error or variation in K_{S-O2} (a.) and K_{S-CH4} (b.) on r; yedoma lakes in winter (—), yedoma lakes in summer (— · — ·), non-yedoma lakes in winter (— ·· — ··) and non-yedoma lakes in summer (-----).