**Bubbles trapped in arctic lake ice: Potential implications for methane emissions**

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[1] The amount of methane (CH4) emitted from northern lakes to the atmosphere is uncertain but is expected to increase as a result of arctic warming. A majority of CH4 is thought to be released through ebullition (bubbling), a pathway with extreme spatial variability that limits the accuracy of measurements. We assessed ebullition during early and late winter by quantifying bubbles trapped in the ice cover of two lakes in a landscape with degrading permafrost in arctic Sweden using random transect sampling and a digital image processing technique. Bubbles covered up to ~8% of the lake area and were largely dominated by point source emissions with spatial variabilities of up to 1056%. Bubble occurrence differed significantly between early and late season ice, between the two lakes and among different zones within each lake (p < 0.001). Using a common method, we calculated winter fluxes of up to 129 ± 486 mg CH4 m−2 d−1. These calculations are, on average, two times higher than estimates from North Siberian and Alaskan lakes and four times higher than emissions measured from the same lakes during summer. Therefore, the calculations are likely overestimates and point to the likelihood that estimating CH4 fluxes from ice bubble distributions may be more difficult than believed. This study also shows that bubbles quantified using few transects will most likely be unsuitable in making large-scale flux estimates. At least 19 transects covering ~1% of the lake area were required to examine ebullition with high precision in our studied lakes.


1. Introduction

[2] Methane (CH4) is a radiatively important atmospheric trace gas currently responsible for approximately 20% of the greenhouse effect [Cicerone and Oremland, 1988; Forster et al., 2007]. Its atmospheric mixing ratio is due to the balance of production and emissions from a wide range of sources and losses to sinks. The quantitative importance of many source components are poorly understood which contributes to large uncertainties in process level understanding of the budget of atmospheric CH4. It is known that freshwater systems, predominantly wetlands, emit large amounts of CH4 to the atmosphere [Denman et al., 2007]. In spite of this, lakes and, in particular small lakes and ponds at high latitudes have seldom been considered potentially major contributors to global and regional carbon (C) cycles nor have they been intensively studied [Bastviken et al., 2004; Zhuang and Reeburgh, 2008]. Estimates suggest a global flux of 8–103 Tg CH4 yr−1 from lakes alone, equal to 5%–30% of all natural emissions [Bastviken et al., 2004, 2011]. Recent models also indicate that natural lakes are twice as abundant globally as previously estimated and smaller in size, predominantly composed of water surfaces less than 1 km2 [Downing et al., 2006].

[3] The abundance of lakes in postglacial permafrost peatlands is twelve times higher than in non-glaciated unfrozen terrain [Smith et al., 2007]. This has recently been considered of great importance in global CH4 budgets because of the larger scale of changes due to arctic warming of permafrost landscapes often rich in organic C [Tarnocai et al., 2009]. CH4 emissions are likely to increase from northern lakes due to warming, extensive permafrost thaw and subsequent C transport into aquatic systems [Cole et al., 2007; Tranvik et al., 2009].

[4] Ebullition (bubbling) represents a highly variable pathway, both spatially and temporally, that can dominate CH4 emissions from surface waters. Bubbles from anoxic lake sediments are a gas mixture with high CH4 concentrations up to 95% [Fendinger et al., 1992; Keller and Stallard, 1994; Casper et al., 2000]. There are only a few studies of ebullition in high latitude lakes [Bastviken et al., 2011] and the accuracy of flux extrapolations is limited by insufficient statistical characterizations of the spatial and temporal variability of bubbling events [Bartlett and Harris, 1993]. However, although less frequently studied, northern lakes provide a unique opportunity to examine the frequency and patchiness of ebullition because bubbles are trapped in lake ice during winter.
Ongoing research conducted by the Pan-Arctic Lake-Ice Methane Monitoring Network (PALIMMN) and by other investigators [e.g., Walter et al., 2006] has taken advantage of trapped bubbles in lake ice to examine the spatial distribution of bubbling events. Together they associated different bubble morphologies with various flux magnitudes and distinguished three different emission patterns: background ebullition, point source and hot spot. Background ebullition, frequently trapped in lake ice and seen as non-layered isolated smaller bubbles, has been related to lower emission rates and younger Holocene-aged sediments. Point sources are thought to be less abundantly occurring although they are more persistent sources of bubbles. These are associated with fixed or relatively fixed points of emission and characterized by higher CH4 fluxes, presumably formed deeper in older organic rich sediment. Point source emissions generate distinct layered bubble morphologies in lake ice where higher fluxes are seen as larger clusters containing merged bubbles. Extremely high fluxes from fixed pockets, hot spots, in the sediments are rare but bubbling rates can possibly be high enough to maintain open holes in the ice near erosional margins of thermokarst lakes [Walter et al., 2006].

Furthermore, Walter Anthony et al. [2010] present a method to infer and quantify fluxes on northern lakes by multiplying the number of emission patterns with their corresponding estimated flux magnitudes. The method has been used across ice covered lakes in Alaska and in the yedoma region of Northern Siberia where point source morphologies and hot spots were quantified using two to six 50 m × 1 m survey transects per lake. Subsequently, the results were used as variables in large-scale flux extrapolations suggesting a release of 24.2 ± 10.5 Tg CH4 yr⁻¹ from all lakes north of 45° [e.g., Walter et al., 2007]. This corresponds to roughly 25%-50% of the total annual global lake flux estimates [e.g., Bastviken et al., 2011].

The objectives of this study were to determine the distribution and spatial variability of trapped bubbles across two ice covered lakes in northern Sweden. We surveyed the lakes in both early and late winter, quantifying the percent area underlain by bubbles and number of point sources. A random sampling design was used with a total of 882 observations along 86 transects after which field estimates were checked and revised if needed using a digital image processing technique. Additionally, we investigated the depth dependence of bubbling events during winter and calculated fluxes from point sources using the method and flux magnitudes as determined by Walter Anthony et al. [2010]. Results were compared between early and late season lake ice, between local subhabitats and with previous studies. Finally, we examined relationships between number of observations and the uncertainty in point source quantifications.

2. Methods

2.1. Site Description

The present study focused on two lakes situated within a dynamic landscape with sporadic discontinuous permafrost, more exactly on the Stordalen Mire, at 68°21′N, 19°02′E, located 11 km east of Abisko in northern Sweden (Figure 1). The mire complex consists of palsas (raised and drained ombrotrophic plateaus underlain by permafrost), semi-wet ombrotrophic areas and wet minerotrophic fens surrounded by shallow lakes [Malmer et al., 2005; Kokfelt et al., 2009]. The climate is subarctic with a mean annual temperature of 0.07°C and 308 mm of precipitation at Abisko (20-year mean; 1986–2006). Callaghan et al. [2010] report warming temperatures in the Abisko region over the past decades that are correlated with increased average active layer depth, later freezeup and earlier break up of lake ice. In the Stordalen Mire the loss of permafrost is resulting in degrading palsas and expansion of existing wet areas [Christensen et al., 2004; Johansson et al., 2006].

The two lakes are 351 m above sea level and 11 m above the nearby lake Torneträsk. Inre Harrsjön is a shallow lake with an approximate area of 0.023 km² (2.3 ha) and a maximum depth of 5 m. Mellan Harrsjön is smaller and covers approximately 0.011 km² (1.1 ha) with a maximum depth of 7 m. Water enters Mellan Harrsjön from the catchment’s mainstream and from Yttre Harrsjön (Figure 1). Inre Harrsjön, on the other hand, has no surface water inlet but receives water from the mire during high flow [D. Olefeldt, personal communication, 2010]. Apart from the most easterly part of Inre Harrsjön, where the palsa is almost in direct contact with the lake margin, the two lakes are surrounded by wet fens dominated by Eriophorum angustifolium, Carex rostrata and Sphagnum spp. Both lakes have abundant aquatic species in their shallow waters. Potamogeton alpinus and Myriophyllum alterniflorum dominate in Inre Harrsjön. However, neither species is found in Mellan Harrsjön which instead is dominated by Sparganium hyperboreum and Hippuris vulgaris in shallower depths down to 1.5 m [plant identification by F. Keuper, personal communication, 2010].

2.2. Sampling Technique

Percent areas of the ice underlain by bubbles (bubble area coverage) and number of bubble clusters per unit area (point source density) were measured and counted across each of the two lakes using a random transect sampling technique. Surveys were made in April 2009 before spring thaw and in October 2009 approximately one week after freezeup. We removed snow from the ice surface along 30 m × 1 m linear transects using a shovel and the bubble area coverage and point source density were quantified within a 0.64 m² quadrat (Figure 2a) that was placed every third meter along each transect. When needed, water was poured onto the ice surface to improve transparency (Figure 3d). Quadrats over opaque ice were excluded from the analysis. Three holes were drilled along each transect through which the water depth was measured from the ice surface using a marked sounding rope with a weight. Depths between sounding points were linearly interpolated. Observations were also made regarding ice thickness and transparency, submerged aquatic plants, and judgments of whether bubbles were shallowly or deeply trapped in the ice or whether they could be related to photosynthesis. Photosynthetic bubbles were morphologically distinct clouds of small bubbles that were closely associated with green aquatic vegetation.

Bubble morphologies were characterized based on the classification scheme (A, B, C and Hot spot) presented in the PALIMMN methods protocol (http://ine.uaf.edu/werc/wp-content/uploads/2010/04/IceSurvey.pdf). Type A clusters were small, usually <30 cm in diameter, with multiple layered
single bubbles (Figure 3a). Type B clusters were larger, usually >30 cm in diameter, with multiple layers of predominantly (>50%) merged bubbles (Figure 3b). The largest Type C clusters were also stacked but with a closed-ice surface, usually >40 cm in diameter (Figure 3c). Background ebullition was classified as isolated bubbles or bubbles in clusters without layers.

The majority of our transects extended from the shoreline toward the center of each lake (Figure 1), a point established using a map and triangulating lines from stable objects surrounding the lakes. The transects’ starting points were randomly chosen from the center point using a compass and a random number generator, ranging from 1 to 360. On the larger Inre Harrsjön additional transects were made to cover areas in the center of the lake. The number of transects was statistically determined using cumulative curves of both bubble area coverage and point source density, plotted for each bubble classification by successive averaging of current and previous transect averages (Figure 4). On each lake we continued to add additional transects until all curves approached an asymptotic value, determined as having five successive averages with a coefficient of variation (CV) lower than 10%. In April, this accuracy was reached after 23 transects on Inre Harrsjön and 20 transects on Mellan Harrsjön. An equal number of transects were made in October, but placed differently because of the randomization of the starting points.

2.3. Digital Image Processing

High resolution photos were taken of each quadrat observation to digitally revise field estimations of bubble area coverage. Photos, particularly those showing clear dark ice, was adjusted in Adobe Photoshop to display bubble patterns as white pixels and surrounding ice as black pixels (Figure 2b). Furthermore, the program’s built-in histogram calculated the number of both black and white pixels thus a highly accurate percent area was obtained.

2.4. Statistics and Flux Estimates

Survey-specific averages, standard deviations (SDs) and CVs of bubble area coverage and point source density were calculated for each specific bubble classification, both on a per lake basis and in 1 m depth intervals, using the total number of quadrat observations within each survey. The variability among different parts of each lake and among depth intervals was tested by comparing transect averages and quadrat observations, respectively, using analysis of variance (ANOVA). Furthermore, to determine whether the bubble area coverage and point source density differed significantly between early and late season lake ice and between the two lakes, data from all four surveys were combined in a
general linear model (GLM). Several tests were made in which overall bubbling and each specific bubble classification was tested separately. All tests used a significance level of 5% ($\alpha = 0.05$).

We estimated survey-specific CH$_4$ fluxes (mg CH$_4$ m$^{-2}$ d$^{-1}$) from our quantified point sources by multiplying their average spatial densities and SDs with the daily flux magnitudes associated with each cluster type as determined by Walter Anthony et al. [2010]. Furthermore, our many transects allowed statistical assessments of such flux estimates by determining the uncertainties when point sources are quantified using any randomly chosen $n$-combination of transects. In this case, calculations were made with the April data from Mellan Harrsjön that were integrated over the whole ice covered season and had the largest variabilities in point source density. We used Matlab (R2008a) to calculate all possible average point source densities by generating all 2-combinations up to all 19-combinations (without duplicates) from the 20 transect averages. Three sets were generated, one for each cluster type. Within every group of $n$-combinations, the probability of reaching the 95% confidence interval, calculated using all 205 observations along the 20 sampled transects of our April survey, was equivalent to the fraction of the point source densities that averaged within that range.

3. Results

3.1. General Observations

The ice cover was mostly clear black ice with occasional opaque patches. Its thickness differed substantially over the year; in October it was approximately 10 cm, compared to 80–90 cm in April. Distinct shallowly suspended point source emissions frequently stretched 20–30 cm below the ice surface. Occasionally, large Type B clusters stretched further. Although clusters were observed deeper in the ice, bubbles, both background ebullition and those of point sources, were estimated to cover larger areas close to the ice surface. No hot spots were found in either of the lakes.

Some observed bubble patterns were omitted from the analysis because they likely contained O$_2$ from photosynthesis. Such possible O$_2$ bubbles, which looked like a dispersed fizz, were abundant in ice over shallow water along the southern and southwestern shore of Inre Harrsjön and in close association with the dense occurrence of *M. alterniflorum*. The fizz morphology could be a result of gas production and release from broadly dispersed, small but consistent sources, such as through the stomata or pores of leaves during overpressurization due to photosynthesis. In contrast, the gases released from sediment sources depend on episodic releases of accumulations of larger gas volumes. Compared to Inre Harrsjön, fizz bubble morphologies were absent in the shallow waters of Mellan Harrsjön in which no *M. alterniflorum* was found.

3.2. Distribution and Within-Lake Variability of Bubbles

The survey-specific overall bubble area coverage averaged from 2.4%–7.7% of the studied lake areas and the point source density from 1.3 to 1.7 clusters m$^{-2}$ (Table 1). Combined, trapped point source emissions represented 84%–96% of the areas underlain by bubbles. Type A clusters accounted for 35%–67% type B and C clusters for 21%–50% and 2%–21%, respectively, and background ebullition for the remaining 4%–16%.

The survey-specific variability in the overall bubble area coverage and point source density had maximum CVs of 190% and 135% (Table 1). Among individual point sources, the lowest variabilities were accounted for by Type A clusters with maximum CVs of 202% and 166% in bubble
area coverage and point source density, respectively. The highest were accounted for by Type C clusters with maximum CVs of 1056% and 1007%.

On the transect scale, the overall bubble area coverage and point source density differed significantly among different parts of Inre Harrsjön in October ($p = 0.002$ and $0.001$, $n = 249$) and among different parts on Mellan Harrsjön (both surveys, $p < 0.001$, $n = 205$), but were homogeneously distributed on Inre Harrsjön in April ($p = 0.592$ and $0.151$, $n = 224$). The most frequent bubbling occurred in the northern and southern part of Mellan Harrsjön with transect averages as high as 22% and 3.9 clusters m$^{-2}$ in bubble area coverage and point source density, respectively. No such distinct zones of frequent bubbling were found in Inre Harrsjön in which the southernmost part experienced least frequent bubbling with a few transect averages close to zero.

3.3. Between-Month and Between-Lake Variability

The total overall bubble area coverage differed significantly with two times larger averages in April than in October and 1.4 times larger averages on Mellan Harrsjön than on Inre Harrsjön ($p < 0.001$, $n = 882$; Figures 5a and 5b). These differences were mainly accounted for by Type A and B clusters which averaged three and 1.7 times larger areas in April ($p < 0.001$ and 0.004, $n = 882$) and by Type B clusters.
which averaged 2.5 times larger areas on Mellan Harrsjön ($p < 0.001$, $n = 882$). At the same time, background ebullition averaged 1.4 times larger areas on Inre Harrsjön ($p = 0.045$, $n = 882$).

[22] In contrast to the above, the total overall average point source density did not differ significantly between October and April nor did it differ significantly between the two lakes ($p = 0.057$ and 0.266, $n = 882$; Figures 5c and 5d). In spite of this, Type A clusters averaged 1.3 times higher density on Inre Harrsjön ($p = 0.015$, $n = 882$) but these clusters were generally smaller than those on Mellan Harrsjön. Type B clusters averaged 0.4 times lower density

**Figure 4.** Lake-specific cumulative curves of (black circles) bubble area coverage and (white circles) point source density, plotted in April by successive averaging of transect averages, for (a, b) background ebullition, (c, d) Type A clusters, (e, f) Type B clusters, and (g, h) Type C clusters. Note the different scales on the y-axes.

**Table 1.** Survey-Specific Averages and CVs in Bubble Area Coverage and Point Source Density

<table>
<thead>
<tr>
<th>Lake</th>
<th>Survey</th>
<th>$n$</th>
<th>Overall</th>
<th>B.g. Ebul.</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
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<tbody>
<tr>
<td>IH‡</td>
<td>October</td>
<td>249</td>
<td>2.4</td>
<td>190</td>
<td>0.4</td>
<td>1.0</td>
<td>0.5</td>
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<tr>
<td>IH‡</td>
<td>April</td>
<td>224</td>
<td>4.8</td>
<td>135</td>
<td>0.4</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>MH‡</td>
<td>October</td>
<td>204</td>
<td>3.4</td>
<td>130</td>
<td>0.3</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>MH‡</td>
<td>April</td>
<td>205</td>
<td>7.7</td>
<td>136</td>
<td>0.3</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>IH‡</td>
<td>October</td>
<td>249</td>
<td>1.25</td>
<td>135</td>
<td></td>
<td>1.02</td>
<td>1.19</td>
</tr>
<tr>
<td>IH‡</td>
<td>April</td>
<td>224</td>
<td>1.64</td>
<td>102</td>
<td></td>
<td>1.83</td>
<td>1.38</td>
</tr>
<tr>
<td>MH‡</td>
<td>October</td>
<td>204</td>
<td>1.50</td>
<td>131</td>
<td></td>
<td>0.95</td>
<td>1.66</td>
</tr>
<tr>
<td>MH‡</td>
<td>April</td>
<td>205</td>
<td>1.63</td>
<td>106</td>
<td></td>
<td>0.92</td>
<td>1.46</td>
</tr>
</tbody>
</table>

§Sum of calculated averages (all bubble classifications).

*Background ebullition.*

‡IH denotes Inre Harrsjön.

MH denotes Mellan Harrsjön.
on the surface of Inre Harrsjön \((p < 0.001, n = 882)\) even though they were similar in size to those observed on Mellan Harrsjön.

3.4. Depth Dependence of Bubbles

The overall bubble area coverage and point source density decreased with depth in the April survey on Mellan Harrsjön. Here, they averaged 13.6% and 1.7 clusters m\(^{-2}\) over 0–1 m compared to 3.7% and 0.7 clusters m\(^{-2}\) over 5–7 m \((p = 0.002\) and 0.005, \(n = 43)\). The differences were predominantly accounted for by Type A clusters which averaged eight times larger area coverage and six times higher spatial density over the shallower interval. In the three remaining surveys no such depth dependency was found. However, Type C clusters were absent at depths > 4 m in all four surveys.

3.5. Flux Estimates From Point Sources

Using data from all transects, the survey-specific overall fluxes ranged from 44 ± 241 to 129 ± 486 mg CH\(_4\) m\(^{-2}\) d\(^{-1}\) (Table 2) with averages of 59 ± 308 and 87 ± 363 mg CH\(_4\) m\(^{-2}\) d\(^{-1}\) (4 ± 19 and 5 ± 23 mmol m\(^{-2}\) d\(^{-1}\)) from the October and April distributions, respectively. Between 16 and 19 transects, covering 1% and 1.2% of the lake area, were needed for robust estimates of point source density (high likelihood of being within the 95% confidence interval determined from all 20 sampled April transects on Mellan Harrsjön; Figure 6). If data from just a few transects were used, the estimated fluxes could be substantially biased. The range of possible fluxes could be up to 18 times higher when calculated from point sources using a combination of only two transects compared to 19 transects.

4. Discussion

4.1. Distribution and Within-Lake Variability of Bubbles

Bubbling events are abundantly evident in the ice on the two studied lakes. The occurrence of point source morphologies (Type A, B and C clusters) suggests organic rich sediments, but not as rich in labile organic sediments to produce CH\(_4\) hot spots as has been observed in yedoma terrains. Nevertheless, the domination of point source patterns in the ice (84%–96% of the survey-specific area that was underlain by bubbles) suggests that emissions are largely dominated by these persistent bubbling events. This corresponds to North Siberian thaw lakes where point source emissions (hot spots excluded) were estimated to account for 77% of the total CH\(_4\) bubble flux during winter [Walter et al., 2007].

The large spatial variabilities in overall bubble area coverage and point source density suggest large inconsistencies and wide spread dispersal of bubbles across the lakes. This corresponds to the patchiness of ebullition observed in previous studies during both winter and ice free periods [e.g., Walter et al., 2006]. Moreover, the substantially higher spatial variabilities of the less frequently occurring Type B and C clusters (CVs of up to 358% and 1056%, respectively) than of the smaller Type A clusters (CVs of up to 202%) support assumptions that large gas releases are highly sporadic and difficult to sample in ice free periods. However, in some parts of the lakes where these large gas releases occur more frequently (see below) the probability of successful sampling is increased.

The significant differences in bubble area coverage and point source density among transects on Inre Harrsjön and Mellan Harrsjön suggest that emissions are irregularly distributed across each lake surface. This further suggests differences in sediment characteristics or bubble accumulation and release. Also, the insignificant difference among transects in Inre Harrsjön in April indicates that bubbling events can be more homogeneously distributed. The large percent area underlain by bubbles in the southern part of Mellan Harrsjön probably relates to increased organic loading. The catchment’s mainstream flowing into the lake most likely transports fine particulate organic carbon (POC) that settles out when the water velocity decreases as the stream flows into the larger water volume of the southern part of the...
lake. Trapped bubbles occurred frequently in the northern part of Mellan Harrsjön near the inflow from Yttre Harrsjön, possibly due to a similar focusing of POC deposition.

4.2. Between-Month and Between-Lake Variability

[28] The significantly smaller bubble area coverage in October was most likely due to new, thin ice cover. In April, the substantially thicker ice contained more trapped bubbles, predominantly due to larger Type A and B clusters, because they have had more time to accumulate. Occasionally, Type B clusters stretched into thin, continuous tubes or were found as interrupted sequences deep into the ice. However, the majority of point sources represented shorter events of ebullition, predominantly trapped within the top 30 cm. Clustered bubble morphologies, indicating point source emissions, are most likely shaped by episodic, yet recurring, gas releases and should not be associated with a continuous flux. Because bubbles were trapped at various depths in the ice, ebullition presumably continues during winter although emission rates seem to decrease as sediment temperature drops.

[29] The significantly smaller bubble area coverage on Inre Harrsjön indicates that ebullition can be highly variable between local subhabitats. The significantly larger area coverage of bubbles on Mellan Harrsjön, predominantly due to significantly higher spatial density of Type B clusters, suggests higher CH₄ fluxes from thicker and more organic rich sediments. In contrast, the significantly larger area coverage of background ebullition and significantly higher density of Type A clusters on Inre Harrsjön suggest lower fluxes and gas formation closer to the sediment surface. These significant differences might be related to the differences in water inflow. The lack of continuous surface water inflows in Inre Harrsjön might contribute to lower C inputs than in Mellan Harrsjön. In Inre Harrsjön, the long-term average accumulation of organic carbon has been estimated to be 15 g m⁻² yr⁻¹ [Kokfelt et al., 2009]. Unfortunately, no comparisons can be made because there is no corresponding sediment record in Mellan Harrsjön.

4.3. Depth Dependence of Bubbles

[30] The majority of studies associating decreasing ebullition with increasing water depth have almost exclusively been made during summer periods [e.g., Bastviken et al., 2004]. However, the depth dependence of winter ebullition remains uncertain. The significantly smaller bubble area coverage and lower point source density over deep water in April on Mellan Harrsjön correspond to the general hypothesis suggesting decreasing probability of lake ebullition with depth [e.g., Bastviken et al., 2004]. It is important to note that this outcome was predominantly accounted for by the significantly larger area coverage and higher density of Type A clusters in ice over shallow water (0–1 m). However, the unexpectedly small bubble area coverage and low point source density in many shallow parts of the lakes in three of our four surveys suggest that there is no clear overall depth dependence of winter bubble accumulation in the ice of our studied lakes. This could be explained by low sediment temperatures at all depths during winter. Compared to deep water sediments, shallow sediments near the lake margin cool more rapidly in early winter affecting CH₄ production because methanogenesis is temperature dependent [e.g., Zeikus and Winfrey, 1976]. Hence, there is a prediction of a zonation of trapped bubbles in lake ice. Ice over shallow sediments will most likely have more bubbles near the surface (early ice) whereas bubbles are more evenly distributed in ice over deeper sediments.

[31] Although Type B and Type C clusters were both homogeneously distributed with depth, the latter were absent at depths >4 m. Sediments at these depths seem to lack

### Table 2. Survey-Specific CH₄ Fluxes (mg CH₄ m⁻² d⁻¹), Calculated From Our Average Point Source Densities Using the Class-Specific Flux Magnitudes Estimated by Walter Anthony et al. [2010]

<table>
<thead>
<tr>
<th>Lake</th>
<th>Survey</th>
<th>Overall</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>IH</td>
<td>October</td>
<td>52 ± 322</td>
<td>8 ± 20</td>
<td>15 ± 66</td>
<td>29 ± 236</td>
</tr>
<tr>
<td>IH</td>
<td>April</td>
<td>44 ± 241</td>
<td>11 ± 19</td>
<td>19 ± 83</td>
<td>14 ± 138</td>
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<tr>
<td>MH</td>
<td>October</td>
<td>65 ± 295</td>
<td>8 ± 21</td>
<td>43 ± 113</td>
<td>14 ± 161</td>
</tr>
<tr>
<td>MH</td>
<td>April</td>
<td>129 ± 468</td>
<td>8 ± 18</td>
<td>49 ± 115</td>
<td>72 ± 354</td>
</tr>
</tbody>
</table>

*Sum of calculated fluxes from all three point source classifications. Errors are the SD in point source density multiplied by the error in flux magnitude.

IH denotes Inre Harrsjön.

MH denotes Mellan Harrsjön.
pockets from which large or more continuous bubbling events occur, presumably because they receive a lesser amount of labile organic loading, thereby sustaining lowered rates of methanogenic activity. This corresponds to emissions from large point sources and hot spots in Alaska and North Siberia which were observed in shallow waters near erosional margins of thermokarst lakes [Walter et al., 2006].

4.4. Flux Estimates From Point Sources

[32] The average whole winter flux from our intensively studied ice covered lakes of 87 ± 363 mg CH₄ m⁻² d⁻¹ is two times higher than whole lake point source fluxes (October–May) from ice covered North Siberian thaw lakes (as estimated by Walter et al. [2006]) and almost four times higher than preliminary summer flux observations. For our two lakes, the flux from June–September 2009 was 23 ± 87 mg CH₄ m⁻² d⁻¹ (mean and SD of n = 1023 fluxes measured using 30 bubble traps) [M. Wik and P. Crill, unpublished]. Furthermore, our early winter average of 59 ± 308 mg CH₄ m⁻² d⁻¹ is roughly two times higher than the average October flux from ice covered Alaskan lakes, estimated by Walter Anthony et al. [2010]. It is considered unlikely that winter emissions exceed those during summer. Also, even though the palsas in the Stordalen Mire complex appear to be thawing and there is mass wastage evident at some sites around the ponds it is unlikely that Stordalen lake sediments receive a sufficient amount of organic loading to sustain CH₄ releases larger than those observed from eroding thermokarst lakes.

[33] One possibility for our high winter fluxes might be that the previously measured flux magnitudes for different point source classes, especially those associated with Type B and C clusters, were not representative for the ebullition in our studied lakes. Based on bubble distribution in the ice, point source emissions seem to be highly episodic during winter. Hence, the assumption of continuous high frequency ebullition causes overestimates. Fluxes from ice covered lakes to the atmosphere should strictly equal the CH₄ release from the ice when it thaws and this is not equivalent to freshly released bubbles. The amount of CH₄ that can be potentially emitted at ice out is a function of ice thickness, trapped bubble volume and concentration. There is some speculation that trapped bubbles are depleted in CH₄ due to dissolution and oxidative processes in the water column while they are frozen into the ice. According to Walter et al. [2006], trapped bubbles have on average a 33% lower CH₄ concentration compared to freshly released bubbles. However, this might vary among local subhabitats, primarily due to the rate at which the ice thickens. A rapidly growing ice cover limits both dissolution and microbial oxidation before bubbles are fully enclosed. Subsequent to entrapment, there is also the possibility of leakage through cracks both to the atmosphere and dissolution back into the water.

[34] Alternatively, the lower flux estimates in North Siberia and Alaska might be related to differences in sampling techniques. Bubble surveys carried out according to the PALIMMN protocol use three 50 m × 1 m non-interrupted transects across each lake surface to quantify trapped bubbles. In our surveys, 150 m² translates to 187 quadrat observations along 17 randomly distributed but interrupted 30 m × 1 m transects. Even on smaller lakes like Mellan Harrsjön (1.1 ha), such dispersed coverage might not be adequate to accurately quantify the spatial density of all three point source classifications (Figure 6). Because trapped bubbles occur irregularly with significant spatial variabilities it is important that the monitored lake area fraction is large (~1% in our lakes) and well distributed in numerous parts of the lake, particularly when quantifying large persistent bubbling events. For example, if the average spatial density of Type B clusters was quantified in three different parts of Mellan Harrsjön using any random combination of three of our 20 sampled transects the average point source density could range between 0.1 and 1.1 clusters m⁻² (Figure 6). This would yield a flux uncertainty that is approximately six times higher than if 17 transects were used. Bubbles quantified using a small number of transects may lead to highly uncertain CH₄ flux estimates.

5. Conclusions

[35] Bubbling events trapped in the ice during winter can cover substantial areas across lake surfaces, predominantly comprised of highly spatially dispersed point source morphologies which becomes substantially more variable and less densely occurring with increasing cluster size (Table 1). Bubble accumulation in the ice continues with decreasing rates through winter, contributing to larger area fractions of bubble patterns before ice out (Figure 5). This suggests that late winter ice surveys are more representative when attempting to quantify winter ebullition over the whole ice covered season. The significant differences in ebullition between our two lakes indicate that ice bubble distributions can be highly variably among local subhabitats, highlighting the difficulty in large-scale extrapolations. Similar to observations around margins of thermokarst lakes [e.g., Walter et al., 2006], the bubble production and release in our studied lakes seem to be linked to zones that may receive larger inputs of labile organic matter, in this case through surface water inflows.

[36] Based on the bubble distributions, we cannot conclude that there is a clear depth dependence in the overall winter ebullition in our studied lakes. Although the C input to the deep centers might be inadequate to produce large gas releases (i.e., those forming Type C clusters), methanogenesis around the lake margins may be inhibited to a greater extent than in deep sediments during winter, most likely by low temperatures. On the other hand, our two studied lakes might be too shallow to observe bubble distributions that do not have an average decrease with depth.

[37] The calculated bubble fluxes from our point source distributions (Table 2) are considered overestimates for our studied lakes. We conclude that CH₄ emission rates cannot be adequately estimated based on bubble morphology methodologies calibrated using flux measurements associated with different point source classifications. Because clusters of point source emissions were seen to occur episodically and with decreasing vertical accumulation as the ice column thickens they should not be associated with year-round continuous fluxes.

[38] Presumably, more accurate estimates and extrapolations of CH₄ fluxes at ice out can be made using the area underlain by bubbles. Using our method, a combination of random transect sampling and digital image processing, bubble morphologies can be measured with high precision
across ice covered lakes. This also includes accurate estimates of background ebullition which might contribute substantially to total emissions. However, flux estimates based on bubble area coverage requires lake-specific measurements of bubble volume and concentration, e.g., sampling various bubble morphologies by melting or crushing blocks of ice [Boereboom et al., 2010].

Our random transect sampling with a large number of statistically determined transects shows that the large spatial variabilities of emission patterns (Table 1) are not easily captured in ice bubble distributions (Figure 4). Regardless of whether an interrupted or continuous transect sampling technique is used as a tool to distribute observations across lake ice each individual transect should be considered one single observation, although the final resolution and accuracy is determined by the total number of independent observations along each transect. Regarding the fact that lake bubble distributions can vary significantly among different zones, ice surveys are preferably made using a large number of short but well distributed transects rather than a small number of longer transects. An insufficient number of transects can be less dispersed on a lake surface, which most likely jeopardizes the accuracy of bubble quantifications and subsequent large-scale flux extrapolations aiming to reduce uncertainties in the budget of atmospheric CH4.

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