Impact of atmospheric pressure variations on methane ebullition and lake turbidity during ice-cover

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Scientific Significance Statement

Methane ebullition from ice-covered lakes is an important contributor to atmospheric greenhouse gases. Ebullition can also have a negative impact on lake water quality. However, despite the global abundance of seasonally ice-covered lakes, there is a lack of continuous, high-frequency ebullition data during ice-cover, and consequently the factors controlling ebullition are unknown. We have collected a 1-month, high frequency record of ebullition using an autonomous echo sounder mounted below the ice. The record shows that ebullition occurs almost exclusively when atmospheric pressure drops below a threshold that is approximately equal to the long-term average pressure. The ebullition intensity is proportional to the amount by which the pressure drops below this threshold. We also show that episodic ebullition events are the cause of previously unexplained turbidity fluctuations.

Abstract

Methane ebullition (bubbling) from lake sediments is an important methane flux into the atmosphere. Previous studies have focused on the open-water season, showing that temperature variations, pressure fluctuations, and wind-induced currents can affect ebullition. However, ebullition surveys during the ice-cover are rare despite the prevalence of seasonally ice-covered lakes, and the factors controlling ebullition are poorly understood. Here, we present a month-long, high frequency record of acoustic ebullition data from an ice-covered lake. The record shows that ebullition occurs almost exclusively when atmospheric pressure drops below a threshold that is approximately equal to the long-term average pressure. The intensity of ebullition is proportional to the amount by which the pressure drops below this threshold. In addition, field measurements of turbidity, in conjunction with laboratory experiments, provide evidence that ebullition is responsible for previously unexplained elevated levels of turbidity during ice-cover.

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Data Availability Statement: Data and metadata are available in Dryad repository at https://datadryad.org/stash/share/45pLzejmUwiAdM5P78iR_Aq4htqCIZN9SUjF8U8.

Additional Supporting Information may be found in the online version of this article.

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Lakes are an important source of atmospheric methane (Wik et al. 2016), and ebullition from lake sediments is often the dominant source of this methane (Bastviken et al. 2004; Sanches et al. 2019). However, there are large uncertainties in measuring and predicting methane ebullition (Engram et al. 2020). Multiple environmental factors affect ebullition, including wind-induced currents (Joyce and Jewell 2003), short wave radiative flux (Wik et al. 2014), sediment temperature variations (Fechner-Levy and Hemond 1996), water level fluctuations (Harrison et al. 2017), and atmospheric pressure changes (Scandella et al. 2011; Varadharajan and Hemond 2012). Most studies of ebullition have been conducted during the open-water season, when these processes often act simultaneously, rendering it difficult to discriminate between them. Ice-cover provides the opportunity to study ebullition under less complicated conditions. However, the paucity of ebullition data during ice cover constitutes a major knowledge gap, despite the prevalence of ice-covered lakes (Verpoorter et al. 2014; Denfeld et al. 2018).

In addition to contributing to atmospheric methane, ebullition from sediment can impact the local aquatic system. When bubbles migrate through sediment, they enhance pore-water advection (Santos et al. 2012), mobilize and release contaminants (Fendinger et al. 1992), and cause sediment destabilization (Kavcar 2008). As they emerge from the sediment, bubbles can entrain sediment particles in their wake, increasing turbidity in the water column (Klein 2006). While ebullition appears to enhance turbidity during ice cover (Lawrence et al. 2016; Tedford et al. 2019a), continuous and simultaneous measurements of ebullition and turbidity have not previously been made.

We examine a 1-month record of ebullition collected during ice cover at Base Mine Lake, in Alberta, Canada. During this period, water level fluctuations, temperature changes, and wind-induced currents were minimal, allowing us to focus on the relationship between atmospheric pressure variations and ebullition. A downward facing echo sounder was mounted below the ice to monitor ebullition continuously from a fixed area. This high frequency ebullition data revealed the dominant effect of atmospheric pressure on ebullition. We also investigated the impacts of ebullition on lake turbidity with the aid of laboratory experiments and field measurements.

Methods

Base Mine Lake (57°11’N, 111°37’W in Alberta, Canada) was formed by filling a mined-out oil sands pit with tailings and capped with water (Dompierre and Barbour 2016). As part of a remediation strategy, the deposition of tailings was completed at the end of 2012. The tailings were 25–35% solids by weight, with similar mean particle size and clay fraction as the fine-grained muds found in lakes and estuaries (Dompierre and Barbour 2016). These tailings are commonly referred to either as fluid fine tailings, or simply mud. The lake exhibits seasonal thermal stratification similar to that of natural dimictic lakes, and ice-cover is typically from November to April (inclusive) also similar to natural lakes in the region (Tedford et al. 2019a).

At the end of 2012, the 7.8 km² lake was 7 m deep, overlying a 45 m mud layer. The initial depth of the water-cap was designed to isolate the mud from resuspension due to the direct action of wind-wave induced currents (Lawrence et al. 1991). The mud layer has been settling gradually over time (Dompierre and Barbour 2016). By January 2018, the average depth of the water-cap was about 10 m (Fig. 1a). Degeneration of residual hydrocarbon inside the mud layer produces methane (Francis 2020); subsequently, bubbles rise through the mud layer and then the water-cap (Fig. 1b). These bubbles are typically 0.1–1 cm diameter when they reach the water surface.

In the present study, we use meteorological data, echo soundings, bottom-water temperature, and turbidity measurements from Day 40 (09 February) to Day 67 (08 March) of 2018 (Zhao et al. 2021). Meteorological data, including atmospheric pressure, have been collected at the central platform (P1) since October 2012 (Fig. 1a), and at the Fort McMurray Airport (369 m above mean sea level), since December 1999 (Environment and Climate Change Canada, Fort McMurray CS). The variations in atmospheric pressure at these two stations were nearly identical (Fig. 2a). However, no pressure data were obtained from P1 between Day 40 and Day 47; therefore, we used the airport data for our analysis.

A downward facing, single-beam echo sounder (Echologger EA400) was deployed on 08 February 2018 at D04 (Fig. 1a) and recovered after ice-off in May. The instrument was suspended 3 m below the ice and 6 m above the lake bed. Bursts of 50 pings over 25 s (2 Hz) were logged once every hour. The instrument was powered by onboard batteries and recorded full profiles of echo intensity internally. With a 5° beam width, the echo sounder monitored an area of 0.5 m radius when deployed 6 m above the bottom. A sample echogram is shown in Fig. 1b. The stability of the ice and lack of strong currents resulted in particularly clear traces of the rising bubbles (diagonal lines in Fig. 1b) as well as a stationary bed (horizontal line at 9 m in Fig. 1b). The diagonal lines indicate rising bubbles with a speed of roughly 22 cm s⁻¹. This rise velocity is consistent with the 0.1–1 cm diameter bubbles observed at the surface (Clift et al. 2005). To estimate ebullition intensity (Fig. 2a), the floating reflectors (the near horizontal lines in the Fig. 1b) are filtered out and then the backscatter intensity (decibels) between a depth of 5.2 and 8.5 m is averaged over the entire 25 s burst. Although the single beam and internal logging of the Echologger EA400 allows for long autonomous deployments under the ice, it does not record bubble locations, or size, inside the beam. Therefore, it is unable to convert ebullition intensity into volumetric methane flux as in the case of dual beam echo sounders (Ostrovsky et al. 2008).
Turbidity was measured at 30-min intervals using a RBRDuo logger with a Seapoint turbidity sensor attached to a mooring chain at P2 (Fig. 1a). The total water depth at this location was approximately 11 m. The turbidity in NTU units was approximately twice the total suspended solids concentration in mg L$^{-1}$ (Tedford et al. 2019a). On 03 October 2019, images of the lake bed were taken using a drop camera, Subsea Video Systems S-513, to facilitate our understanding of ebullition and turbidity.

**Results**

Variations in atmospheric pressure, ebullition intensity, turbidity, and bottom-water temperature under ice from 09 February 2018 (Day 40) until 08 March 2018 (Day 67) are presented in Fig. 2. Ebullition intensity varies dramatically from hour to hour. The most intense ebullition events occurred during the passage of two low-pressure systems. The first system persisted from Day 43 to Day 45, and the second from Day 54 to Day 60 (Fig. 2a). During the first event, ebullition started to increase when the atmospheric pressure dropped below its long-term average, increased further as the pressure continued to drop, and then decreased as the pressure increased. Ebullition essentially ceased when the atmospheric pressure rose above its long-term average again. During the second event, the pressure cycled down and up three times and ebullition peaked during each pressure trough. During periods of above average pressure, ebullition either ceased altogether, or occurred in occasional bursts with no clear connection to atmospheric pressure.
Increased turbidity (decreased water clarity) at depth is typically associated with low-pressure events (Fig. 2c). During the first event (Day 43–45), a peak in turbidity at 8.5 m coincided with a pressure trough and high ebullition. During the second event (Day 54–60), there were three troughs in the atmospheric pressure and three corresponding peaks in ebullition intensity. Turbidity at 8.5 m peaked during the second and third pressure troughs, but did not peak during the first pressure trough on Day 54 even though ebullition peaked. Whereas, turbidity at 2.5 m was not affected by ebullition or pressure. Note, the bottom-water temperature has no apparent correlation with ebullition (Fig. 2d).

We conducted preliminary laboratory experiments to investigate the link between ebullition and turbidity. Following the procedures outlined in Zare and Frigaard (2018), we prepared a layer of Carbopol, a transparent gel-like material, as a surrogate for the mud. We capped the Carbopol with a layer of water to mimic Base Mine Lake (Fig. 3). We injected air through a needle, 0.6 mm in diameter, into the base of the Carbopol and observed the rise of the resulting bubbles. As the bubbles rose through the water-Carbopol interface, some of the Carbopol, as well as fine particles placed on the interface, were entrained into the wake of the bubbles (Fig. 3a). Some of the entrained Carbopol and fine particles detrain before the bubbles rise to the water surface (Fig. 3b). We hypothesize that the same process occurs in Base Mine Lake. Turbidity at depth was affected by ebullition (8.5 m in Fig. 2c), whereas higher in the water column it was not affected (2.5 m in Fig. 2c). After the passage of many bubbles, a conduit formed within the Carbopol (Fig. 3c). Some of the overlying water (blue) entered the conduit after the release of each bubble.
Photographs of the lake bed (Fig. 4) show conduits through which methane bubbles emerge, similar to those observed in the laboratory (Fig. 3), and in natural lakes where they cause crater-like depressions in the lake bed known as “pockmarks” (Bussmann et al. 2011). These pockmarks are of different sizes and are distributed unevenly over the lake bed. Pockmark 1 (Fig. 4a) has an outer diameter of about 1 cm and a smaller inside conduit of approximately 2 mm diameter. Similar conduit sizes have been observed in the laboratory (Kavcar 2008) and the ocean (Torres et al. 2002). The pockmarks have different depths, diameters, and varying spatial distribution. For example, pockmark 8 (Fig. 4d) is much larger than pockmark 1, and presumably more gas has passed through it, resulting in greater erosion. On the other hand, pockmark 3 (Fig. 4b) is limited in depth and diameter, indicating that it is a younger pockmark. The variety of pockmarks shows that ebullition can gradually modify the morphology of the lake bed. The uneven distribution of pockmarks creates challenges for the monitoring of ebullition. The images in Fig. 4 were selected because they have pockmarks, with Fig. 4c representing the densest pockmark distribution observed. However, the majority of the images of the lake bed had no pockmarks. Recall that the echo sounder only monitors approximately 0.8 m²; if the echo sounder was deployed above an area without active pockmarks, ebullition would not likely have been recorded.

**Discussion**

While many researchers have observed a relationship between pressure variations and methane ebullition from sediments (Walter Anthony et al. 2010; Harrison et al. 2017), to our knowledge none have observed as definitive a relationship as we have presented in Fig. 2. Our data set is special for two reasons. First, given that the lake is ice-covered, and there are no inflows or outflows, pressure variations in the sediment are almost exclusively due to atmospheric pressure fluctuations. Second, by mounting an echo sounder in the ice, we were able to obtain a continuous record of ebullition from a fixed location for an extended period of time.

In our data record, the ebullition intensity is well approximated by:
E_P \approx \frac{k}{P_{th} - P}, \quad \text{if } P < P_{th}, \quad \text{otherwise}

(1)

where $E_P$ is the predicted ebullition intensity, $P$ is atmospheric pressure, $P_{th}$ is a threshold pressure, and $k$ is a proportionality constant. As a measure of the goodness of fit between the measured ebullition, $E_M$, and the ebullition predicted by Eq. 1, we use $Q = 1 - \frac{\sum (E_M - E_p)^2}{\sum E_M^2}$. The variation of $Q$ with $P_{th}$ and $k$ is plotted in Supporting Information Fig. S1. The optimal value of $Q = 0.87$ is obtained when $P_{th} = 97.1$ kPa and $k = 2.9$ dB/kPa. Applying this set of values, the result from Eq. 1 is shown in Fig. 2b. It matches the magnitude and timing of observed ebullition well. An alternative set of values is obtained using the average atmospheric pressure $P_{th} = P_{ave} = 96.9$ kPa, and $k = 4.2$ dB/kPa, calculated by equating the time integral of the observed ebullition intensity over the study period with the time integral of the predicted ebullition intensity using Eq. 1. This latter pair of values gives $Q = 0.79$ as shown in Supporting Information Fig. S1. A comparison between the observed ebullition intensity and predicted ebullition intensity using this pair of values is shown in Supporting Information Fig. S2.

In addition to atmospheric pressure fluctuations, many factors have been suggested to affect methane ebullition. Seasonality in temperature can influence ebullition by affecting methane production rate and methane solubility in pore water (Fechner-Levy and Hemond 1996; DelSontro et al. 2016). The temperature of the surface of the mud in Base Mine Lake can vary several degrees on a seasonal basis (Dompierre and Barbour 2016), in response to the seasonal variation in the temperature of the water column (Tedford et al. 2019a). However, during the study period, the bottom-water temperature remains stable (Fig. 2d) and shows no correlation with ebullition. The temperature inside the mud layer varies even less. Dompierre and Barbour (2016) have shown that temperature...

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Fig. 4. Photographs taken from a camera suspended approximately 5 cm above the water-mud interface on 03 October 2019. (a) An active pockmark (#1) with a narrow conduit within. (b) Two pockmarks (#2–3) located close to each other. Pockmark 2 is backfilled with sediment, indicating bubbles did not rise through it in recent ebullition events. Pockmark 3 is particularly small, potentially because few bubbles have passed through it. (c) Four pockmarks (#4–7) in close proximity. (d) One large pockmark (#8). The instrument (red and black color) on the bottom-left corner of each image is an RBR concerto data logger. The rim of the black guard has a diameter of 8.6 cm. In (b) and (d), the instrument is covered by mud. The location of pockmark 1 is marked as white diamond in Fig. 1a; whereas, the location of pockmarks 2–8 is indicated with a white square in Fig. 1a.
variations inside the mud decreases exponentially with depth and the variations are negligible 4 m below the lake bed. Falling water levels, due to reservoir withdrawals, can also trigger ebullition (Harrison et al. 2017). However, due to the absence of inflow and outflow during ice cover, the water level in Base Mine Lake is stable. Finally, Joyce and Jewell (2003) observed that shear stresses caused by bottom currents, driven by surface winds, can trigger the release of bubbles. However, under ice, wind-driven bottom currents are negligible.

As in natural sediment, ebullition in Base Mine Lake is subject to complex processes. Nevertheless, based on our observations during ice cover and the effectiveness of Eq. 1, we conclude that most of the ebullition in Base Mine Lake can be explained using a relatively small number of principles and assumptions, namely: there is a range of depths within the mud of Base Mine Lake in which the methane concentration in the pore water is at, or near, saturation (Francis 2020); methane bubbles are present in this zone, with sizes ranging from the size at nucleation to a critical size at which ebullition occurs (Algar et al. 2011); and methane released through ebullition is replenished by methanogenesis, but at time scales much longer than the duration of pressure events.

During ice-cover inflows into, and outflows from, the lake are negligible, and the hydrostatic pressure exerted on the mud by the combination of water and ice is constant. Therefore, variations in atmospheric pressure change the pressure exerted on the bubbles within the mud. When the pressure experienced by the bubbles drops, the corresponding reduction in methane solubility (Henry’s law) results in gas moving from the pore water into the bubbles, causing them to grow. Decreasing pressure also causes bubbles to grow (ideal gas law). The idealization represented by Eq. 1 implies that when the atmospheric pressure drops below the pressure threshold (e.g., Fig. 2, Day 43), the largest bubbles reach critical size and ebullition starts. Subsequently, when atmospheric pressure rises above the pressure threshold (e.g., Day 45), the corresponding increase in methane solubility results in methane moving from the bubbles into the pore water. This, together with the reduced volume due to the increased pressure, causes ebullition to stop.

In applying Eq. 1, we have assumed a constant pressure threshold during our study period, and obtained results that are largely consistent with the observations presented in Fig. 2. However, for the pressure threshold to remain constant, the rate of ebullition would need to be in equilibrium with the rate of methane production. If the rate of ebullition exceeds the rate of production, the store of available methane will decrease, effectively reducing the pressure threshold; whereas, if production exceeds ebullition the pressure threshold will rise. The relative success of our assumption of a constant threshold in Eq. 1 implies that the variation of the pressure threshold during our study period was not significant.

While the sediments in Base Mine Lake are the product of a mining operation, they have similar mean particle size and clay fraction as the fine-grained muds found in natural lakes and estuaries (Dompierre and Barbour 2016). The clear linkage between pressure and ebullition that we have observed has also been observed in natural lakes. For example, Mattson and Likens (1990) observed rapid ebullition during low atmospheric pressure events in Mirror Lake, New Hampshire. In northern ice-covered lakes, Walter Anthony et al. (2010) also observed that ebullition responded to atmospheric pressure fluctuations. Scandella et al. (2011) showed a strong relationship between pressure variations and ebullition from the “gassy” sediments in Upper Mystic Lake, Massachusetts.

There are occasions (e.g., during Days 40, 46, 51, and 61 in Fig. 2) when sporadic ebullition occurs even though atmospheric pressure is considerably higher than the pressure threshold. This may be a result of intermittent coalescence of bubbles inside the mud-layer causing them to reach critical size. Movements within the mud layer due to its gradual settling (Dompierre and Barbour 2016) may facilitate coalescence and ebullition.

Ebullition in Base Mine Lake has other important impacts beyond the elevated turbidity shown in Fig. 2c. Our laboratory experiments show that rising bubbles push water out of established conduits, and once the bubbles exit, the water flows back in (Fig. 3c). The same process probably occurs in Base Mine Lake, enhancing the exchange of heat and dissolved contaminants between the mud layer and water column. This process provides an explanation for the enhanced mixing hypothesized by Dompierre et al. (2017) in modeling exchange between the mud and water column. The rising bubbles increase dissolved methane concentration in the water column, which leads to methane oxidation and contributes to decreasing dissolved oxygen concentration (Risacher et al. 2018). In winter, methane bubbles are frozen into the ice, along with hydrocarbon transported from the mud (Tedford et al. 2019b). The presence of bubbles causes weakening of the ice, that is apparent during augering, and may result in earlier melting. In summer, hydrocarbon transported by the bubbles reaches the lake surface, influencing heat exchange with the atmosphere (Chang 2020; Clark et al. 2021) and the properties of wind-generated surface waves (Hurley et al. 2020).

Conclusions

Although there are extensive observations of ebullition during the open-water season, under ice observations are limited. We present high-frequency ebullition data from Base Mine Lake under ice, that reveal that ebullition primarily occurs when atmospheric pressure is below a threshold. This pressure threshold is approximately equal to the average atmospheric pressure. The timing and magnitude of major ebullition events is well reproduced by setting the ebullition

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intensity to be proportional to the pressure deficit below the pressure threshold. Laboratory experiments and field observations also show that these episodic ebullition events elevate turbidity at depth and can enhance exchange of contaminants between the mud layer and the water column.

Even though our results are from a single lake during ice-cover, the importance of atmospheric pressure variations is not limited to this lake, or the ice-cover season. The response of ebullition to pressure variations has been observed in natural lakes, both during ice-cover (Walter Anthony et al. 2010) and during the open-water season (Mattson and Likens 1990; Scandella et al. 2011). Future studies are needed to refine and extend our results to other lakes and the open-water season. Our data suggest that future surveys need to sample ebullition frequently enough (at least hourly) to capture the rapid response of ebullition to pressure variations.

References

Algar, C. K., B. P. Boudreau, and M. A. Barry. 2011. Initial rise of bubbles in cohesive sediments by a process of viscoelastic fracture. J. Geophys. Res. Solid Earth 116: B04207. doi: 10.1029/2010JB008133

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

Bussmann, I., S. Schlömer, M. Schlüter, and M. Wessels. 2011. Active pockmarks in a large lake (Lake Constance, Germany): Effects on methane distribution and turnover in the sediment. Limnol. Oceanogr. 56: 379–393. doi: 10.4319/lo.2011.56.1.0379

Chang, S. 2020. Heat budget for an oil sands pit lake. Master’s thesis. Univ. of British Columbia, Vancouver, Canada. Available from https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0392976.

Clark, M. G., G. B. Drewitt, and S. K. Carey. 2021. Energy and carbon fluxes from an oil sands pit lake. Sci. Total Environ. 752: 141966. doi: 10.1016/j.scitotenv.2020.141966

Clift, R., J. R. Grace, and M. E. Weber. 2005, Bubbles, drops, and particles. Dover.

DelSontro, T., L. Boutet, A. St-Pierre, P. A. del Giorgio, and Y. T. Prairie. 2016. Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity. Limnol. Oceanogr. 61: S62–S77. doi: 10.1002/lo.10335

Denfeld, B. A., H. M. Baulch, P. A. del Giorgio, S. E. Hampton, and J. Karlsson. 2018. A synthesis of carbon dioxide and methane dynamics during the ice-covered period of northern lakes. Limnol. Oceanogr.: Lett. 3: 117–131. doi: 10.1002/lo2.10079

Dompierre, K. A., and S. L. Barbour. 2016. Characterization of physical mass transport through oil sands fluid fine tailings in an end pit lake: A multi-tracer study. J. Contam. Hydrol. 189: 12–26. doi: 10.1016/j.jconhyd.2016.03.006

Francis, D. J. 2020. Examining controls on chemical mass transport across the tailings-water interface of an oil sands end pit lake. Master’s thesis. Univ. of Saskatchewan, Saskatchewan, Canada. Available from https://harvest.usask.ca/handle/10388/12776.

Harrison, J. A., B. R. Deemer, M. K. Birchfield, and M. T. O’Malley. 2017. Reservoir water-level drawdowns accelerate and amplify methane emission. Environ. Sci. Technol. 51: 1267–1277. doi: 10.1021/acs.est.6b03185

Hurley, D., G. Lawrence, and E. Tedford. 2020. Effects of hydrocarbons on wind waves in a mine pit lake. Mine Water Environ. 39: 455–463. doi: 10.1007/s10230-020-00686-7

Joyce, J., and P. W. Jewell. 2003. Physical controls on methane ebullition from reservoirs and lakes. Environ. Eng. Geosci. 9: 167–178. doi: 10.2113/9.2.167

Kavcar, C. P. 2008. Stability of cohesive sediments subject to pore water and gas ebullition fluxes and effectiveness of sand and aquablok caps in reducing the resuspension rates. Doctoral dissertation. The Univ. of Michigan, Ann Arbor, MI. Available from http://hdl.handle.net/2027.42/60885.

Klein, S. 2006. Sediment porewater exchange and solute release during ebullition. Mar. Chem. 102: 60–71. doi: 10.1016/j.marchem.2005.09.014

Lawrence, G. A., P. R. B. Ward, and M. D. MacKinnon. 1991. Wind-wave-induced suspension of mine tailings in disposal ponds—a case study. Can. J. Civ. Eng. 18: 1047–1053. doi: 10.1139/91-127

Lawrence, G. A., E. W. Tedford, and R. Pieters. 2016. Suspended solids in an end pit lake: Potential mixing mechanisms. Can. J. Civ. Eng. 43: 211–217. doi: 10.1139/cjce-2015-0381

Mattson, M. D., and G. E. Likens. 1990. Air pressure and methane fluxes. Nature 347: 718–719. doi: 10.1038/347718b0
Verpoorter, C., T. Kutser, D. A. Seekell, and L. J. Tranvik. 2014. A global inventory of lakes based on high-resolution satellite imagery. Geophys. Res. Lett. 41: 6396–6402. doi: 10.1002/2014GL060641

Walter Anthony, K. M., D. A. Vas, L. Brosius, F. S. Chapin III, S. A. Zimov, and Q. Zhuang. 2010. Estimating methane emissions from northern lakes using ice-bubble surveys. Limnol. Oceanogr.: Methods 8: 592–609. doi:10.4319/lom.2010.8.0592

Wik, M., B. F. Thornton, D. Bastviken, S. MacIntyre, R. K. Varner, and P. M. Crill. 2014. Energy input is primary controller of methane bubbling in subarctic lakes. Geophys. Res. Lett. 41: 555–560. doi:10.1002/2013GL058510

Wik, M., R. K. Varner, K. W. Anthony, S. MacIntyre, and D. Bastviken. 2016. Climate-sensitive northern lakes and ponds are critical components of methane release. Nat. Geosci. 9: 99–105. doi:10.1038/ngeo2578

Zare, M., and I. A. Frigaard. 2018. Onset of miscible and immiscible fluids’ invasion into a viscoplastic fluid. Phys. Fluids 30: 063101. doi:10.1063/1.5024718

Zhao, K., E. Tedford, M. Zare, and G. Lawrence. 2021. Atmospheric pressure influencing ebullition and turbidity, Dryad, [accessed 2021 April 27]. Available from https://doi.org/10.5061/dryad.shqbzkh5t.

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