Permafrost thaw lake methane flux estimates using GPR

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Summary

This research demonstrates a new measurement and scaling approach to constrain the estimates of methane (CH_4) fluxes emitted from permafrost thaw (thermokarst) lakes. Permafrost is estimated to store about 20% of the total terrestrial carbon (C) stock. Permafrost thawing releases C in part as CH_4, however, there are large uncertainties in the global CH_4 budget that limit the accuracy of climate change projections. Estimating how much C is released from permafrost is critical to overcome this knowledge gap. Lake CH_4 fluxes are estimated by combining direct observations, geophysical mapping and satellite remote sensing along with a scaling strategy based on lake expansion rate. This research contributes to advance the understanding of CH_4 fluxes from thermokarst lakes and improve atmospheric C models.

Introduction

Permafrost is estimated to store about 20% of the total terrestrial carbon (C) stock (Schuur et al., 2015). Permafrost thawing releases C in part as methane (CH_4), however, there are large uncertainties in the global CH_4 budget that limit the accuracy of climate change projections. Estimating how much C is released from permafrost is crucial to tackle this issue. In this context, this project aims to constrain the estimations of CH_4 fluxes from permafrost thaw (thermokarst) lakes, helping to reduce the uncertainties quantifying atmospheric CH_4.

After water vapor (H_2O) and carbon dioxide (CO_2), CH_4 is the third most abundant greenhouse gas in Earth's atmosphere. Climate change has the potential to increase CH_4 emissions from permafrost thawing, which would induce more climate warming. The expected results of this positive climate feedback include sea level rise, coastal erosion, ecological migrations, and global scale climate/weather impacts (Schuur et al., 2015). However, these effects are underestimated because this feedback is currently unconsidered on atmospheric C models.

The Arctic and boreal lakes are responsible for about two-thirds of natural CH_4 emissions in the northern region above 50° latitude (Wik et al., 2016), and this estimation tends to increase as a consequence of longer ice-free seasons. Thermokarst lakes are formed when permafrost thaw, subsides, and floods. Thermokarst are estimated to cover about 20% of the northern permafrost region (Olefeldt et al., 2016). Thermokarst lakes usually present a sub-lake permafrost thaw, known as thaw-bulb or talik. As thermokarst lake and talik expand, more permafrost C becomes available for microbial conversion to CH_4. Lakes can emit gas by diffusion, transport by emergent plants and ebullition (bubbling). Ebullition is the process by which the gas bubbles are released to the atmosphere through the lake. Ebullition is the dominant and most challenging to estimate due to its spatial and temporal variability (Walter et al., 2006), and this represents a significant knowledge gap.

The main objective of this research is to demonstrate a new measurement and scaling approach to constrain the estimates of CH_4 fluxes from thermokarst lakes in a local and regional scale. Lake gas fluxes are estimated by combining direct observations, geophysical mapping and satellite remote sensing along with a scaling approach based on lake expansion rate.

Study sites

Figure 1 shows a location map of the three study sites at the North Slope, Alaska. A total of nine lakes were surveyed: one around Utqiaġvik city called Ikroavik lake, five lakes around Teshekpuk lake region, and three lakes around Oumalik region. All sites have historical aerial photos and Synthetic Aperture Radar data available.

The North Slope, Alaska, is on a zone of continuous permafrost. Utqiaġvik and Teshekpuk regions are located on the Outer Coastal Plain of Alaska, where the superficial geology deposit is characterized by glaciomarine sediments. Oumalik region is located on the Inner Coastal Plain of Alaska that it is on a high C-rich Yedoma type permafrost (Kanevskiy et al., 2011) formed during the Pleistocene and, therefore, has a potential for a high CH_4 flux rates.

Methods

The direct observations of lake gas flux follow the methodology described by Walter Anthony et al. (2010), where snow-free or shoveled lakes are crossed by foot following transects perpendicular to the shoreline, and bubble seeps are classified. The amount of seep types per lake are upscaled to estimate CH_4 flux. However, this visual survey approach can be limited if there is snow cover or

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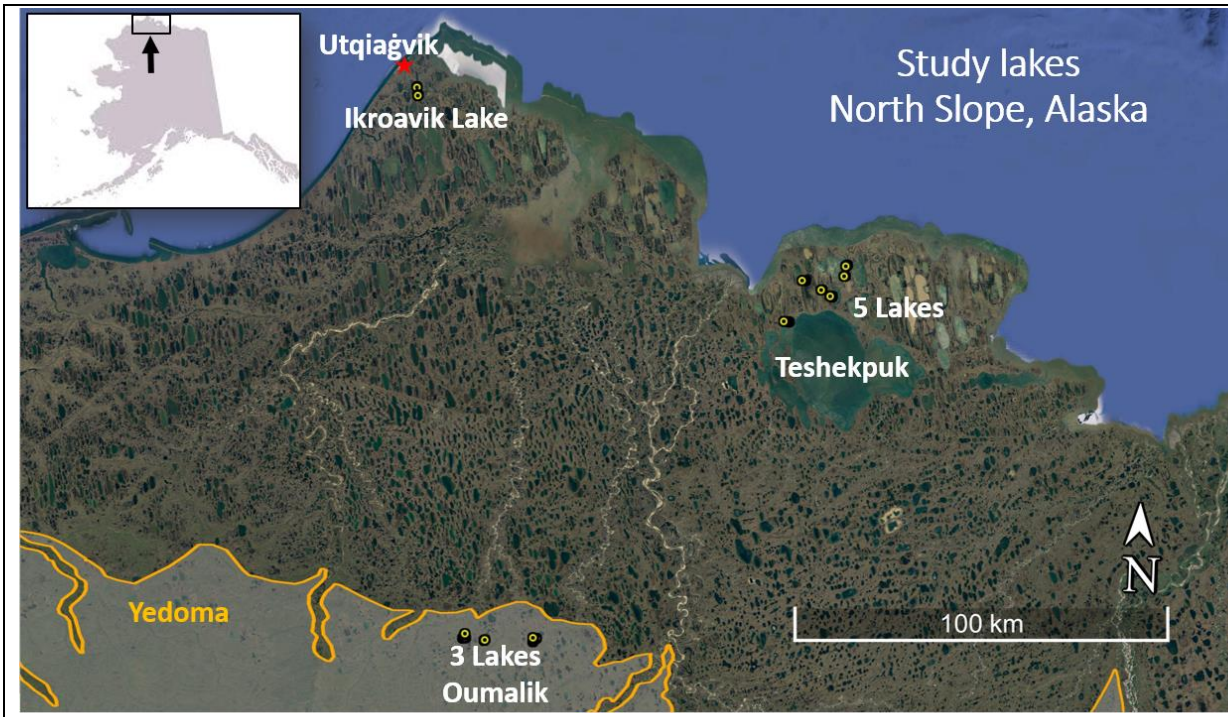

Figure 1: Aerial photo of the North Slope, Alaska, showing the study sites locations. Ikroavik lake around Utqiaġvik city, five lakes around Teshekpuk lake region, and 3 lakes around Oumalik region. Oumalik is on top of Yedoma, which is a carbon-rich type of permafrost formed during the Pleistocene.

white ice because the gas bubbles must be visible on the lake ice surface.

To overcome this limitation, ground-penetrating radar (GPR) can be applied to estimate the amount of ebullition gas present in lake ice (Fantello et al., 2018). This non-invasive geophysical method estimates the volume fraction of gas trapped in ice, allowing to detect gas bubbles in ice even with snow cover or white ice on the lake surface. Fantello et al. (2018) developed a quantitative relationship between GPR wave velocity and gas content. Assuming that CH_4 flux rate from the lake bottom is constant and knowing the ice growth rate based on modeling, we can use the GPR-estimated gas volume in the ice on a given date to estimate CH_4 annual flux rate. The GPR instrument can be towed by a snowmachine, which enables rapid spatial coverage.

Even though GPR measurements can constrain the estimation of gas fluxes trapped in lake ice compared to the visual method, a limited number of lakes can be surveyed. This gap can be filled using Synthetic Aperture Radar (SAR). Engram et al. (2013) showed that L-band SAR can identify gas trapped in lake ice, which can be used to scale ebullition gas fluxes. SAR backscatter signal is affected by frozen gas bubbles, and this effect is proportional to the amount of gas trapped.

Lake expansion rates are calculated based on the method demonstrated by Jones et al. (2011). Publicly available aerial photos from different years are georectified and the lakeshores digitized to calculate the expansion rate for the lakes surveyed. Finally, the field observations results can be combined with the SAR results in order to scale gas flux and establish relationships between lake expansion rates and gas flux estimates.

Results and Discussion

L-band SAR results with low, medium, and high backscatter helped to guide GPR acquisition locations. We specifically targeted transects >200 m on different shoreline directions and lake-center locations that are hypothesized to have different gas emission potential. During the GPR data acquisition, ice thicknesses in drill holes were measured in order to calibrate the ice properties.

Figure 2 show three examples, one for each region, of radargrams (100 m scaled profile) and results of ice thickness and volumetric gas content (VGC). Comparing the results, it is possible to see that the ice thickness varies from 0.87 m to 1.55 m and they show a variable roughness of the ice-water interface. Oumalik lake 2 (Fig. 2c) shows the lowest ice thickness variation, while Naluakruk lake (Fig. 2b) in Teshekpuk region shows ~0.5 m variation over ~20 m distance. In terms of VGC, Oumalik presents a relative higher result, probably because it is on Yedoma type of permafrost that has a high C content.

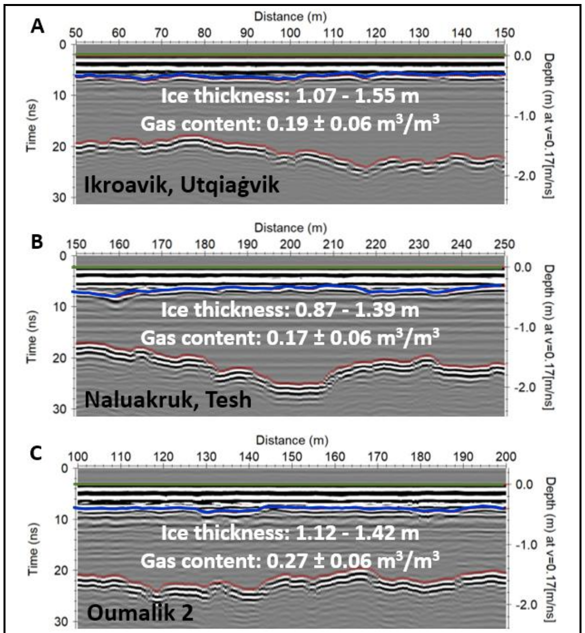

Figure 2: Examples of radargrams showing ice thickness and volumetric gas content results: a) Ikroavik lake at Utqiaġvik region, b) Naluakruk lake at Teshekpuk region, and c) Lake 2 at Oumalik region. In blue is the picked snow and ice interface, and in red is the ice and water interface.

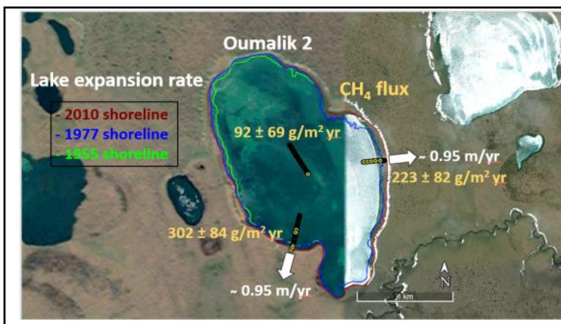

Figure 3: Lake expansion rate and CH_4 flux rate results for Oumalik lake 2. In green is the 1955 georectified lake shoreline, blue 1977, and red 2010. The location of the three GPR transects are shown on the map.

Figure 3 shows the results of lake expansion rate (LER) and CH_4 flux rates for Oumalik lake 2. This lake presents an expansion rate of ~0.95 m/year and a relatively higher CH_4 emission on the margins compared to the lake-center, which is consistent with our hypothesis.

Figure 4 shows the results of LER versus GPR estimated VGC. Although we have LER results for only four lakes so far, it is possible to observe that, in general, lakes in Oumalik region present a higher VGC. Moreover, in general, the east (E) margins present a higher expansion rate, and the north (N) margins present a lower expansion rate. Further analysis of our data will help to shed a light on the relationship of LER and VGC among the different studied regions across the North Slope of Alaska.

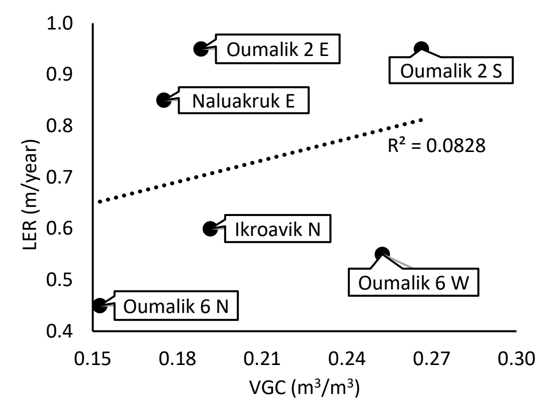

Figure 4: Lake expansion rate (LER) versus GPR estimated volumetric gas content (VGC). N, S, E, and W indicates the lake margin direction where GPR measurements were conduted.

Conclusions

This research helps to constrain the estimates of CH_4 flux emitted from thermokarst lakes by combining direct observation, GPR and SAR methods along with a scaling approach based on lake expansion rate. The results suggest variable regional gas fluxes, in part controlled by the location of C-rich Yedoma permafrost. This study contributes to an improved understanding of CH_4 fluxes from thermokarst lakes that could be used to refine atmospheric C models. Furthermore, a better estimation of CH_4 emissions is essential to project the impacts of climate warming and determine the best management strategies.

Acknowledgments

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