Drivers of methane variability in arctic ponds

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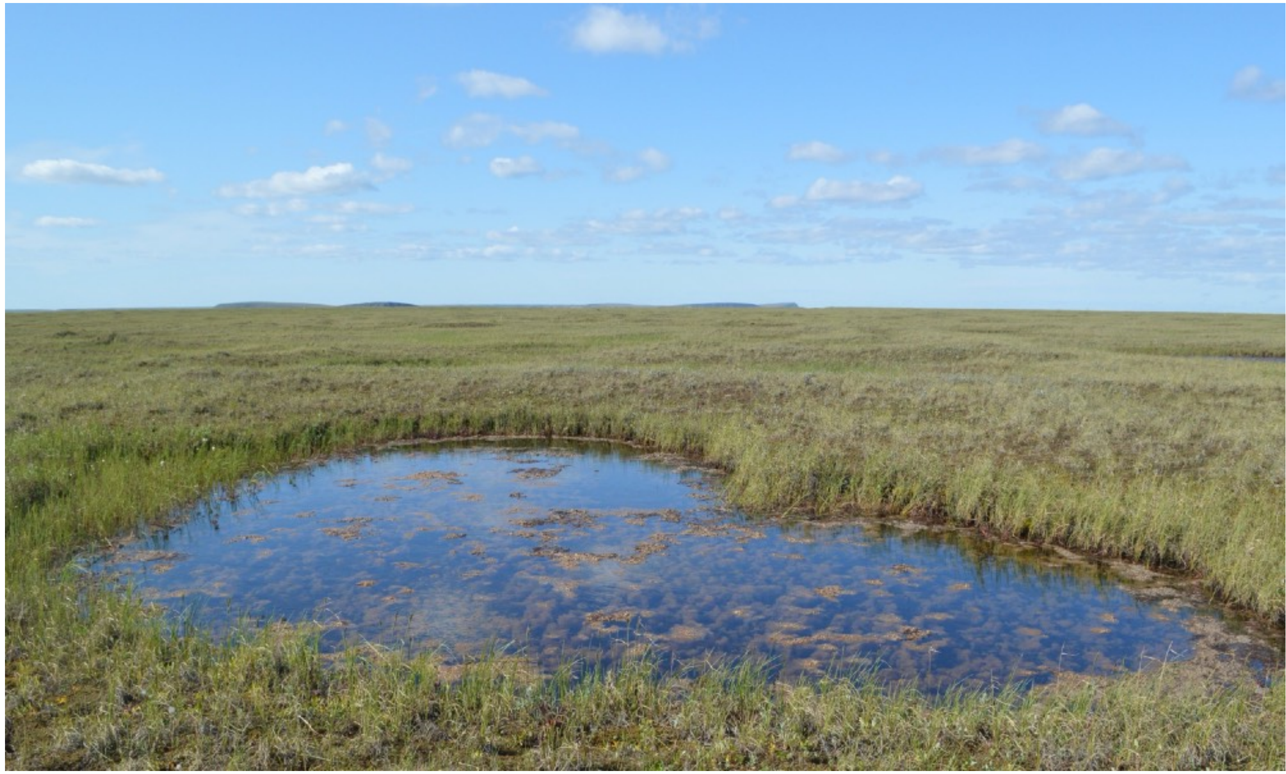
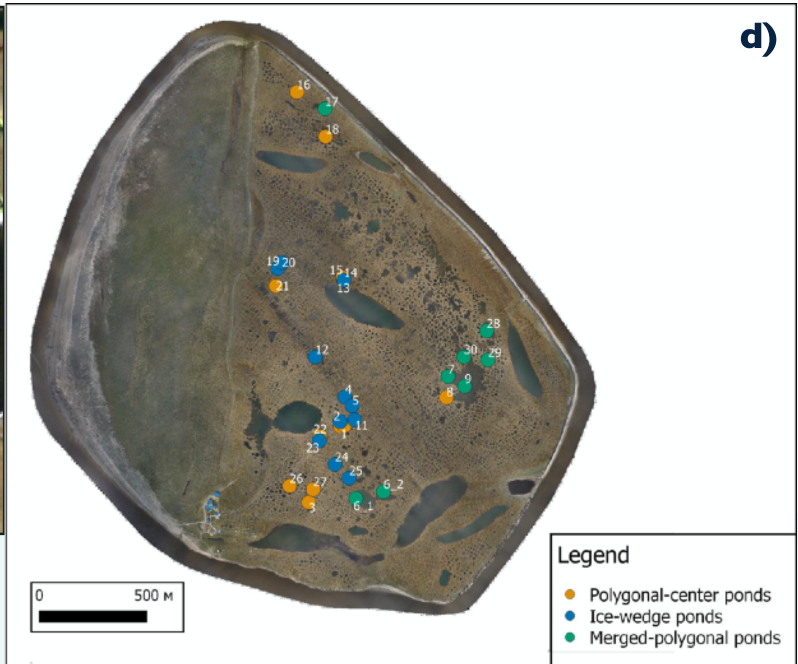


Drivers of methane variability in arctic ponds matter

- Methane (CH_4) emissions from small waterbodies are **significant greenhouse-gas sources**, especially in pan- and circumarctic landscapes [Holgerson and Raymond, 2016; Juutinen et al., 2009; Wik et al., 2016].
- There is growing evidence that global warming will enhance methane emissions from these systems [Aben et al., 2017; Yvon-Durocher et al., 2017].
- Methane emissions and dissolved methane concentrations in ponds are **highly variable** [Juutinen et al., 2009; Laurion et al., 2010; Sepulveda-Jauregui et al., 2015].
- Drivers of pond-to-pond variability include the topography of ponds, substrate availability and present methanogenic communities [DelSontro et al., 2018; DelSontro et al., 2016; Juutinen et al., 2009; Negandhi et al., 2013; Sepulveda-Jauregui et al., 2015]
- **A good grasp on the main mechanisms responsible for spatial variability is essential to improve upscaling and modeling of water methane emissions.**
- Most studies on spatial variability focus on regions in North America and North Europe, and only few studies investigate local variability in methane.
- We focus on spatial variability of methane concentrations in ponds of permafrost-affected landscapes in Eastern Siberia, which
    - which are exposed to the same climate
    - are in close proximity to each other.

41 ponds were measured on Samoylov Island and Kurungakh

- Study took place in the Lena River Delta in Eastern Siberia on the two Islands Samoylov (N 72.3749, E 126.4938) and Kurungakh (N 72.2978,E 126.2068). Study areas are characterized by polygonal tundra and feature many waterbodies.
- Ponds were measured from 2019-07-23 to 2019-08-27, 30 scattered randomly over Samoylov Island and 11 on Kurungakh Island.
- Surface and bottom concentrations of methane and carbon dioxide were determined through gas chromatography.
- Up to four water samples for surface concentration measurements were taken per pond at a time.
- Half of the ponds were measured twice over the measurement period.
- Additionally, environmental variables and geomorphological variables were recorded for each pond.



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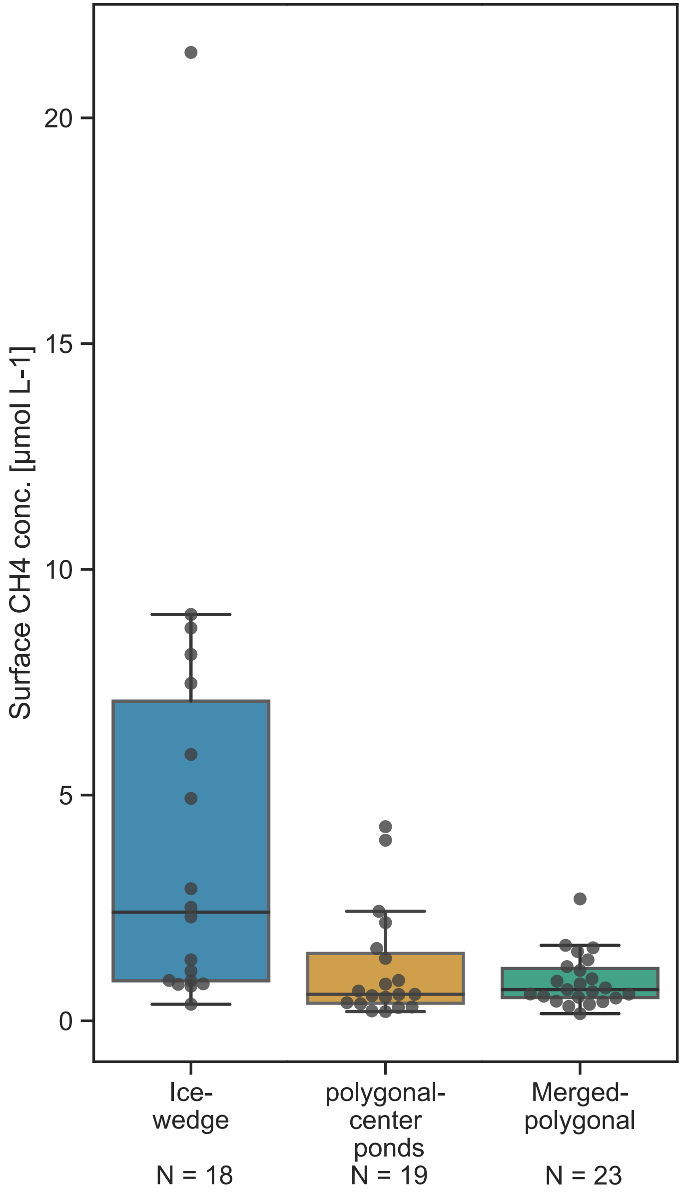
a) & b) © OpenStreetMap



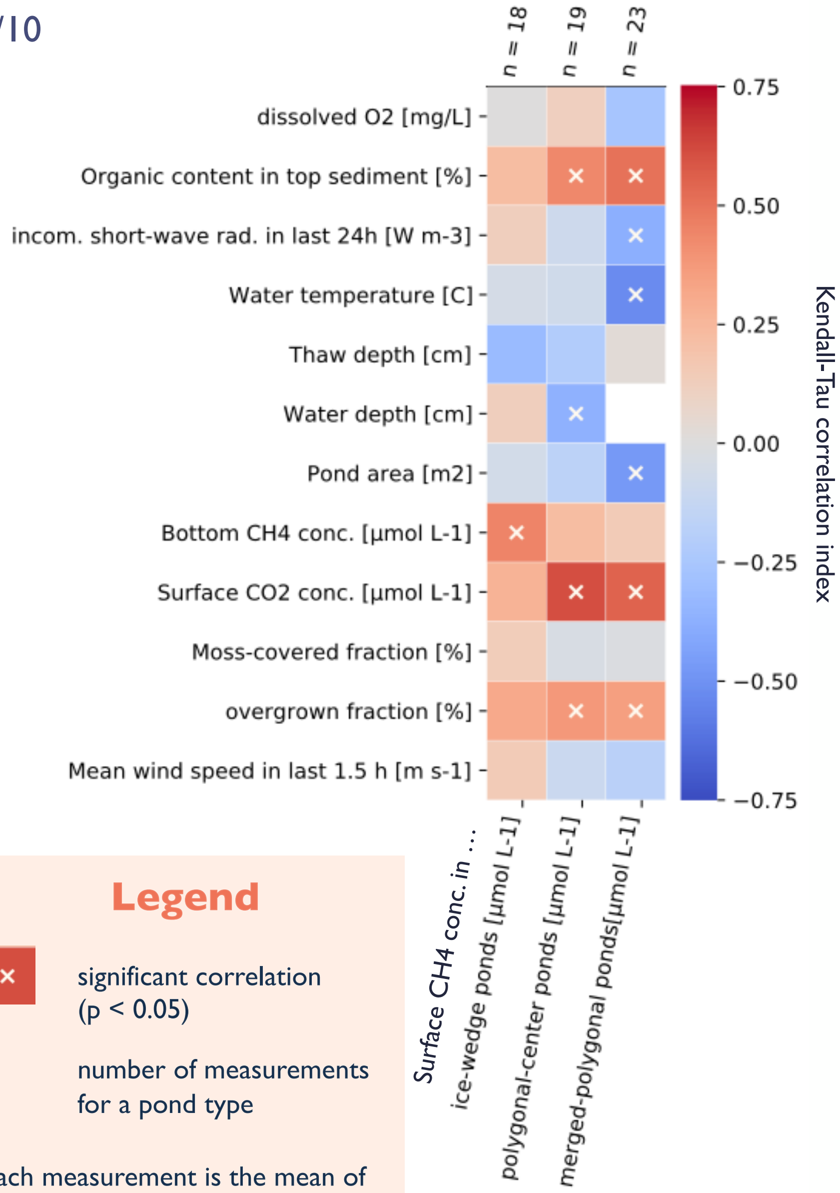
Statistical distributions of CH_4 surface concentrations vary between pond types

- **Ice-wedge ponds** exhibit by far the highest concentrations and the largest spread in the distribution.
- **Polygonal-center** and **merged-polygonal** ponds have a similar range, but merged-polygonal ponds have the least skewed distribution.
- While **ice-wedge** and **polygonal-center** pond bottom methane concentrations exceed surface concentration by a factor of 1.19 and 1.81 respectively, this factor is as small as 0.19 for **merged-polygonal ponds**. This is likely owing to the large surface area and mostly flat, sedimented underground of these ponds leading to a **better mixing**. This could explain why the distribution of surface concentrations is least skewed for **merged-polygonal ponds**.

Ice-wedge ponds
Often narrow, partly underlain by ice

Polygonal-center ponds
water filled, degraded polygon center

Merged-polygonal ponds
several subsided polygons



Legend

× significant correlation ($p < 0.05$)

n number of measurements for a pond type

Each measurement is the mean of 1-4 water samples that were taken within a short time.

Kendall-Tau* correlation of CH_4 surface concentrations with potential drivers

- **Merged-polygonal** and **polygonal-center** ponds are significantly correlated with **organic content** in the (subaquatic) topsoil and with the **fraction of the pond overgrown by vascular plants**. Both of these are indicators of how much carbon is available for methanogenesis.
- Plants are known to increase **substrate quality** thus enhancing methanogenesis in the sediment [Joabsson and Christensen, 2001].

Both merged-polygonal and polygonal-center ponds are limited by carbon availability.

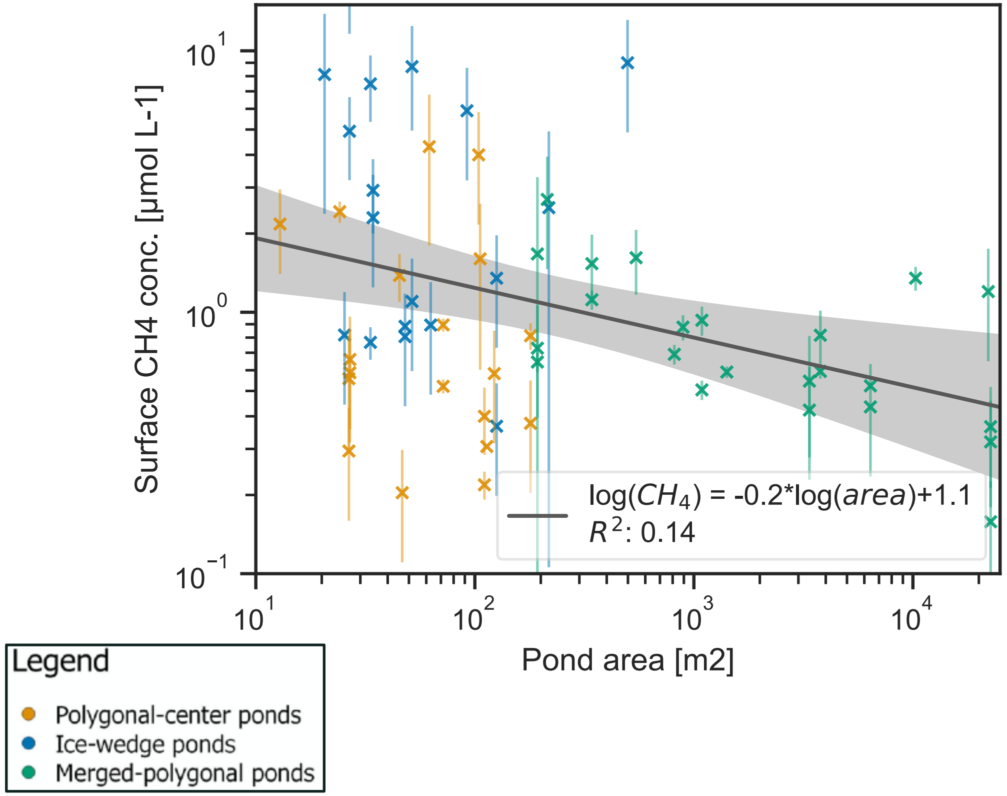
- For both pond types, organic content and overgrown fraction are significantly anticorrelated ($p < 0.05$) with pond area or water depth.

Smaller ponds are richer in organic content.

- While the stratification of **ice-wedge** and **polygonal-center** ponds might mask the influence of environmental variables like water temperature on surface methane concentrations. That **merged-polygonal ponds** significantly correlate to the largest number of variables might be due to their better-mixed state.
- DelSontro et al. [2016] have shown that carbon limitation is able to dampen the temperature dependence of methanogenesis. As the solubility of methane decreases with raising temperatures, this might be the reason for the negative correlation of water temperature and incoming shortwave radiation in **merged-polygonal ponds**. Additionally, since these ponds are the largest, oxidation might show a stronger dependence on temperature than methanogenesis.

* The Kendall-Tau index is a measure of correlation that does not assume the relation to follow a specific function.

The relation between pond area and surface methane concentration holds only for large ponds



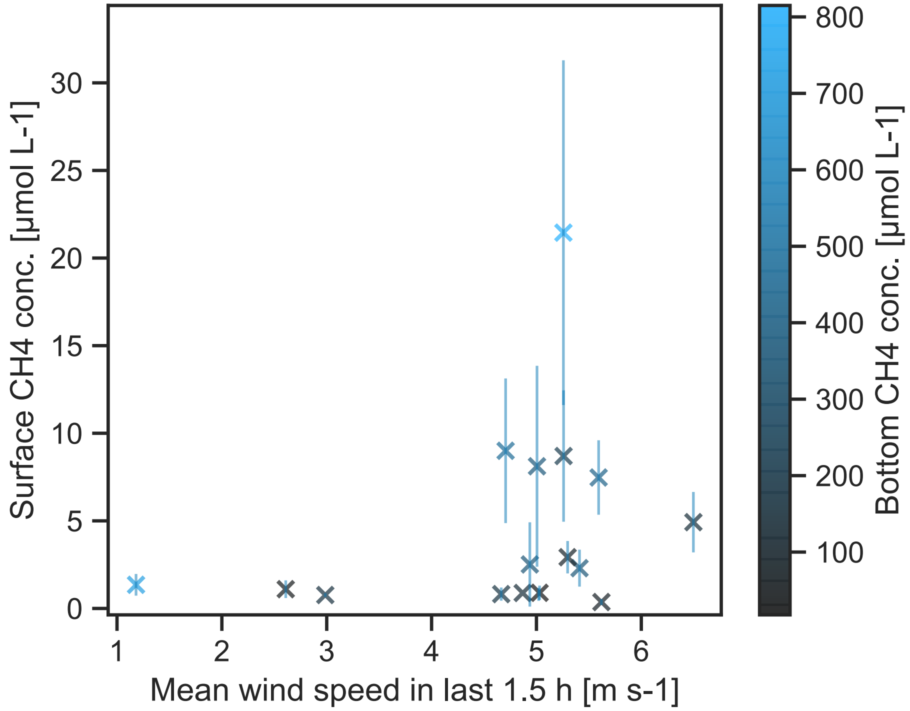
- The relation between surface methane concentration and pond area can be well approximated by $\log([CH_4]) = -0.2*\log(area)+1.1$ for large ponds.
  - This agrees well with the relation found by Polishchuk et al. [2018] ($\log([CH_4]) = -0.26*\log(area)+0.64$) and a general negative correlation also found by Juutinen et al. [2009]; [Wik et al., 2016] among others.

- For small ponds, the deviation from the regression model increases strongly.
  - **Ice-wedge ponds** have stronger-than-expected concentrations.
  - **Polygonal-center ponds** have weaker-than-expected concentrations.
  - Both spread uniformly around area and show only weak relation.

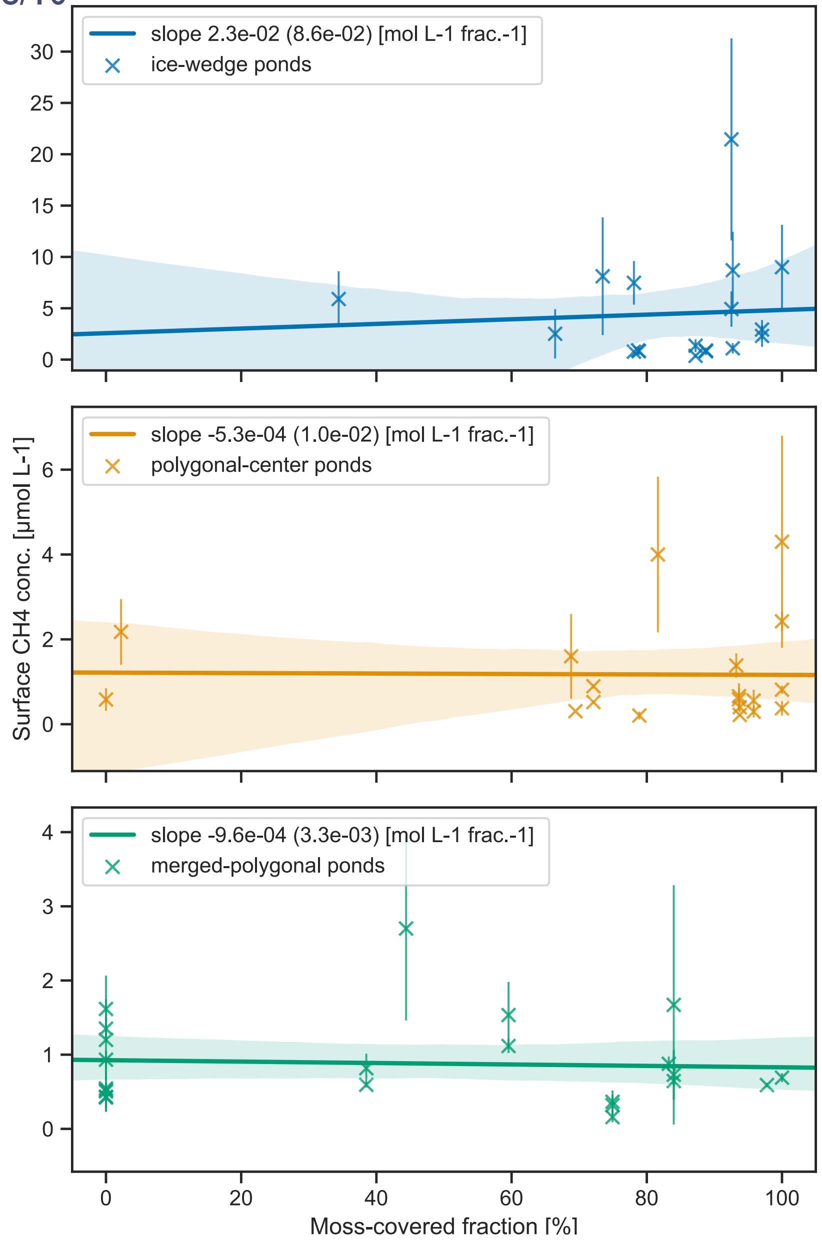
- Rather than area, surface methane concentrations in **polygonal-center ponds** significantly correlate with **water depth** ($p < 0.05$).
  - For this pond type, water depth is only weakly connected to area.
  - Water depth being a better predictor than pond area is in line with findings by Wik et al. [2016].

As a main limit on a) overgrown fraction (apart from methane concentrations the overgrown fraction is only sig. correlated to water depth) and b) oxidation, the water depth is the root cause of the variability in methane in polygonal-center ponds.

Ice-wedge ponds: surface CH_4 concentrations ~ wind speed & bottom CH_4 concentrations



- In **ice-wedge ponds**, the surface concentration tends to be low when **wind speed** is below 4 m/s. In this regime, the pond is **stratified**, because bottom temperatures are much lower than in other ponds ((5.9 +/- 2.5)C versus (9.5+/-2.2)C (mean with standard deviation)).
- With **raising wind speeds** deeper waters with higher concentrations get mixed upwards and then surface concentrations can steeply increase. The strength of this increase mainly correlates with the bottom concentrations – the more methane there is at the bottom, the more gets mixed up (Correlation coeff: a) wind < 4m s-1: 0.3, b) wind > 4m s-1: 0.78).
  - This mechanism is the reason why **ice-wedge ponds** are the only pond type with a positive correlation between surface concentration and wind speed.
- The strong gradient between bottom and surface concentrations makes mixing efficiency important and overshadows other effects. This might be the reason for
  - the **highest concentrations** among the three pond types in **ice-wedge ponds**,
  - the reduced number of significant correlations (surface concentrations correlate only significantly to bottom concentrations).
- Above average concentration in this pond type have also been found by Negandhi et al. [2013] and Laurion et al. [2010], who also found evidence that these ponds emit larger fraction of **old carbon**. This might explain the weaker connection of **ice-wedge ponds** to overgrown fraction.



There is no unambiguous relation between moss-covered fraction and surface methane concentration in any pond type

- Most of the subaquatic soils of the ponds in the study area are at least **partly covered by submerged mosses** (Scorpidium scorpioides). This moss photosynthesises at the bottom of the pond and creates an oxic layer where **methane can be oxidised**. Additionally, the thick moss captures bubbles and thus **suppresses ebullition** [Knoblauch et al., 2015; Liebner et al., 2011].
- The standard error on the slope (in brackets) is an order of magnitude larger than the slope. Thus, the sign of the relation is uncertain.

We do not find that moss cover reduces surface methane concentration on the pond scale.

- However, it inhibits diffusion, if we look at 1D transects. Bottom methane concentrations in the moss layer are on average 1.8 (+/- 1.2) times higher than in open water.
- We hypothesize that
  - moss cover also enhances methanogenesis by providing additional organic substrate as the moss dies. Thus, even though moss leads to enhanced oxidation at the bottom of the pond, the higher **productivity balances out the loss through oxidation**,
  - the accumulation of methane in the moss layer creates a gradient between moss-covered and moss-free areas in the pond. Through **lateral mixing** part of the methane escapes the moss and reaches the surface.

Summary

- **Substrate availability** is an important driver of methane concentrations in **polygonal-center** and **merged-polygonal** ponds.
  - Smaller, shallower ponds tend to be richer in substrate (more organic content in sediment and higher overgrown fraction) and thus exhibit higher concentrations.
  - For **merged-polygonal ponds, area**, which is easier to measure than water depth, is a good predictor of methane concentrations. But for **polygonal-center ponds**, area is only weakly connected to **water depth,** and water depth is a far better predictor.
  - This is in agreement with Juutinen et al. [2009] and Sepulveda-Jauregui et al. [2015], who also found that topography and substrate availability are important predictors.
- **Ice-wedge ponds** are strongly **stratified** as they are narrow, steep and feature a large temperature gradient in summer. If bottom waters are mixed up, surface concentrations spike. Additionally, these ponds tend to be richer in substrate [Laurion et al., 2010; Negandhi et al., 2013].
- We do not find that the **moss-covered fraction** of a pond controls methane surface concentrations, as moss might enhance local methanogenesis by providing substrate and lateral mixing might reduce the dampening effect of moss on diffusion.

Literature

Aben, R. C. H., et al. (2017), Cross continental increase in methane ebullition under climate change, *Nat Commun*, *8*, doi:10.1038/s41467-017-01535-y.

DelSontro, T., J. J. Beaulieu, and J. A. Downing (2018), Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change, *Limnology and Oceanography Letters*, *3*(3), 64-75, doi:10.1002/lol2.10073.

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*(S1), S62-S77, doi:10.1002/lno.10335.

Holgerson, M. A., and P. A. Raymond (2016), Large contribution to inland water CO2 and CH4 emissions from very small ponds, *Nature Geoscience*, *9*(3), 222-U150, doi:10.1038/ngeo2654.

Joabsson, A., and T. R. Christensen (2001), Methane emissions from wetlands and their relationship with vascular plants: an Arctic example, *Global Change Biol*, *7*(8), 919-932, doi:10.1046/j.1354-1013.2001.00044.x.

Juutinen, S., M. Rantakari, P. Kortelainen, J. T. Huttunen, T. Larmola, J. Alm, J. Silvola, and P. J. Martikainen (2009), Methane dynamics in different boreal lake types, *Biogeosciences*, *6*(2), 209-223, doi:10.5194/bg-6-209-2009.

Knoblauch, C., O. Spott, S. Evgrafova, L. Kutzbach, and E. M. Pfeiffer (2015), Regulation of methane production, oxidation, and emission by vascular plants and bryophytes in ponds of the northeast Siberian polygonal tundra, *J Geophys Res-Biogeo*, *120*(12), 2525-2541, doi:10.1002/2015jg003053.

Laurion, I., W. F. Vincent, S. MacIntyre, L. Retamal, C. Dupont, P. Francus, and R. Pienitz (2010), Variability in greenhouse gas emissions from permafrost thaw ponds, *Limnol Oceanogr*, *55*(1), 115-133, doi:10.4319/lo.2010.55.1.0115.

Liebner, S., J. Zeyer, D. Wagner, C. Schubert, E. M. Pfeiffer, and C. Knoblauch (2011), Methane oxidation associated with submerged brown mosses reduces methane emissions from Siberian polygonal tundra, *J Ecol*, *99*(4), 914-922, doi:10.1111/j.1365-2745.2011.01823.x.

Negandhi, K., I. Laurion, M. J. Whiticar, P. E. Galand, X. M. Xu, and C. Lovejoy (2013), Small Thaw Ponds: An Unaccounted Source of Methane in the Canadian High Arctic, *Plos One*, *8*(11), doi:e7820410.1371/journal.pone.0078204.

Polishchuk, Y. M., A. N. Bogdanov, I. N. Muratov, V. Y. Polishchuk, A. Lim, R. M. Manasypov, L. S. Shirokova, and O. S. Pokrovsky (2018), Minor contribution of small thaw ponds to the pools of carbon and methane in the inland waters of the permafrost-affected part of the Western Siberian Lowland, *Environ. Res. Lett.*, *13*(4), 15, doi:10.1088/1748-9326/aab046.

Sepulveda-Jauregui, A., K. M. W. Anthony, K. Martinez-Cruz, S. Greene, and F. Thalasso (2015), Methane and carbon dioxide emissions from 40 lakes along a north-south latitudinal transect in Alaska, *Biogeosciences*, *12*(11), 3197-3223, doi:10.5194/bg-12-3197-2015.

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, *Nature Geoscience*, *9*(2), 99-+, doi:10.1038/ngeo2578.

Yvon-Durocher, G., C. J. Hulatt, G. Woodward, and M. Trimmer (2017), Long-term warming amplifies shifts in the carbon cycle of experimental ponds, *Nature Climate Change*, *7*(3), 209-213, doi:10.1038/nclimate3229.