Reply to Review 1

General comments

This is a relevant study that examines the role of ponds in CO2 and CH4 exchange of polygon tundra in Lena Delta. This research continues the long-term GHG studies conducted by the group at the Lena Delta. The results indicated that when accounting the ponds, the estimate of the tundra's net uptake of CO2 decreased by about ten percentage while the pond and tundra had equal CH4 fluxes, except that there were a CH4 flux hotspot in the pond's shoreline. Researchers focused on a pond, not the wet polygon centers, that are common but smaller landscape features. An eddy covariance measurement system was placed on the shore of a pond formed when polygons were merged. The setting allowed distinguishing and comparing fluxes from the pond and the surrounding tundra. Moreover, wind sector-based inspection showed that some of the pond's shoreline areas were sites of high CH4 fluxes. Data are, however, limited temporally and spatially, i.e. comparison of one pond vs tundra and one growing season. Unfortunately, chamber measurements and ebullition measurements to validate the hotspot's areal features were not conducted. EC methods and data analyzes are adequate. I think that the data deserve to be published, but the current manuscript version is premature.
Overall, the text needs linguistic and stylistic editing, and to my opinion, the current introduction is simplistic and the descriptions of footprint partitioning and the spatial extrapolation for CO2 and CH4 are confusing and wondered why different for the two species. Discussion could be developed to give pointers what the results signify and mean for flux estimation in the area.
I am sure that authors can do a rewrite that will improve the manuscript overall, incl. language, presentation of the data analyzes, and emphasizing the significance of the results in larger context. I have listed some detailed comments below.

> *Thank you very much for your thorough review. We carefully went through all the comments and hope that some of the general comments are already improved thanks to this, especially with regards to the method section. With regards to the introduction, we specified our study object better by differentiating between small water bodies and thermokarst ponds. More precisely, we propose the following addition in line 21:*
> The ponds in this polygonal tundra have formed almost exclusively through thermokarst processes: The ground has a high ice content, so when the ice melts, the ground subsides and thermokarst ponds form (Ellis et al., 2008). These ponds are often only as bis as one polygon, but when several polygons are inundated, larger shallow waterbodies form, which we call merged polygonal ponds (Rehder et al., 2021)
>
> *In the rest of the manuscript, we now use the term 'thermokarst ponds' instead of 'small water bodies'*

Additionally, we propose to include the following paragraph in the discussion (line 336) to embed our study better in the grand scheme of things:

Our results indicate that future eddy covariance flux studies aiming to capture a representative landscape flux should pay extra attention to the waterbodies in their footprint.
The CO_2 flux from ponds has the opposite sign to the tundra, and, consequently, ponds should cover about as much area in the footprint as they do in the larger landscape. In this way, the chances of capturing CH_4 hotspots are also higher, which can then be investigated in more detail. With warming in the Arctic thermokarst ponds might undergo drastic changes through permafrost degradation (Liljedahl et al., 2016). While some studies project a drainage of the landscape (Andresen and Lougheed, 2015), others anticipate enhanced formation of ponds due to thermokarst (Bring et al., 2016), at least on a regional scale. Uncertainty in the future evolution of thermokarst ponds creates a need for a better understanding of these systems.

Lastly, we made many small linguistic and stylistic changes, which will hopefully improve the quality of the manuscript. For the sake of brevity, we will not list all changes here. However, we will of course submit a marked-up PDF with the differences to the new version when submitting a new manuscript.

Specific comments

Check tense throughout the text.

We now consistently use present tense.

l. 22. About lakes and ponds: I suggest 'potential', because the pond vs lake division is not always used

We hope that we understood this comment correctly. Our point here is that ponds emit more methane per area than lakes (see e.q. Holgerson and Raymond (2016); (Wik et al., 2016)). Even though many studies bin water bodies by size, and do not divide between ponds and lakes, we focus only on thermokarst ponds in our study. Ponds are most of the time much better mixed than lakes, often completely, so carbon emission from ponds show different patterns than lakes. We slightly changed the sentence in the manuscript in the following way:
… they have a higher potential than lakes to counterbalance the carbon sink function of the surrounding tundra.

l. 34. Origins of CH4: This likely varies between sites as also in the case of CO2. Sediment mineralization produces gases as well. There are earlier studies to be cited.

To expand more on methanogenesis, we added to following sentences in line 34.
CH_4 is produced in the sub-aquatic soils and anoxic bottom waters (Borrel et al., 2011; Conrad, 1999; Hedderich and Whitman, 2006) . Additionally, CH_4 can also be produced in the oxic water column (Bogard et al., 2014; Donis et al., 2017), though this pathway only becomes significant in large waterbodies (Günthel et al., 2020) and is still under debate (Encinas Fernández et al., 2016; Peeters et al., 2019). During

methanogenesis, CO_2 can also formed as a byproduct (Hedderich and Whitman, 2006).

l. 67. closed-path or enclosed-path?

Thank you for noticing. Of course, the Licor 7200 is an enclosed-path gas analyzer. We changed the word closed to enclosed three times in the method section.

Fig 1. Could you provide a photo of the pond?

Of course. We added a picture at the end of this document, include it in the supplements and refer to this picture in the methods.

l. 127 "is shown as a gray shaded area in Figure 1, c and d" >> here and elsewhere the figure citations can be condensed. e.g. ....cumulative footprint.. (Fig. 1 c-d).

Thank you for this suggestion, we harmonized and condensed all references to figures and tables. See example for l. 127 below.

This sum is referred to as the cumulative footprint (gray shaded area in Fig. 1, c-d)

l. 132. I suggest editing the title. What's a bulk model?

Thank you for this suggestion. We deleted the "bulk model" from the title of the section, the section has now the title:

Gap filling the CO_2 Flux

Additionally, we edited the first sentence of the section for clarification about the bulk model:

To gap-fill the net-ecosystem exchange (NEE) fluxes of CO2, we use the bulk-NEE model by (Runkle et al., 2013).

l. 151. open water and no photosynthetic activity: I understand, but maybe state here that no or only small photosynthetic activity

This is a good suggestion; we altered the sentence as follow:

… we expect little to no photosynthetic activity in the open-water part of the merged polygonal pond.

l. 156. Would it make more sense to include also CH4 here?

Instead of adding a paragraph here, we merge the two paragraphs 2.4.4 Aquatic CO_2 Flux and 2.4.5 Up-scaled CO_2 flux (as suggested by you below) and add another paragraph focusing on methane after line 188:

2.4.5 CH4 flux partitioning

Since we do not have a simple gap filling model at hand for CH_4 emissions from the tundra, and since CH_4 emissions are much more variable than CO_2 emissions, we treat CH_4 differently. Instead of extracting the fluxes from the landcover types, we focus on wind sectors. We divide fluxes from

- *tundra*: At least half of the footprint consists of dry tundra, and the wind direction is larger than 170°.
- *shore*$_{50°}$: Less than 40% of the footprint consists of dry tundra and water contributed to the footprint with at least 30%. The wind direction lies between 30° and 65°.
- *pond*: At least half of the footprint consists of open water and the wind direction lies between 65° and 110.

- *shore$_{120°}$*: Less than 40% of the footprint consists of dry tundra and water contributed to the footprint with at least 30%. The wind direction lies between 110° and 130°.

l. 160. Bulk model? Is this a common expression or should it be clarified?

We followed your suggestion and combined it with your comment on line 132. We now write "bulk model" in cursive to clarify that it is a name of the model given by Runkle et al. 2013 and not a common expression. We edited the name of the model throughout the text.

l.163. in a second step > second, following sentence a bit complicated

Thank you for pointing out this sentence. We tried to simplify the sentence as follows:
Second, we assume that the total, observed flux is a linear combination of the fluxes from the land cover types weighted by their respective contribution to the footprint.

l. 181-182. I suggest combining with the previous chapter. Something wrong in the first sentence?

As mentioned above, we followed your suggestion and combined the two sections. Additionally, we simplified the sentence in l. 180 as follow:
To evaluate the impact of ponds on the landscape CO_2 flux, we estimate a polygonal-tundra landscape-CO_2 flux ($F_{Landscape}$) by linearly combining ponds and semi-terrestrial tundra…

l. 197 > Could add the means as well.

Thank you for this comment. We added the CO2 flux-mean from the two sectors in front of the standard deviation.

l.210. Could you mark the shoreline sectors on the map?

The figure of the study site was already relatively full of information. Therefore, we decided to mark the shoreline sectors on a small map and added it to figure 6. Please see below the new figure 6.

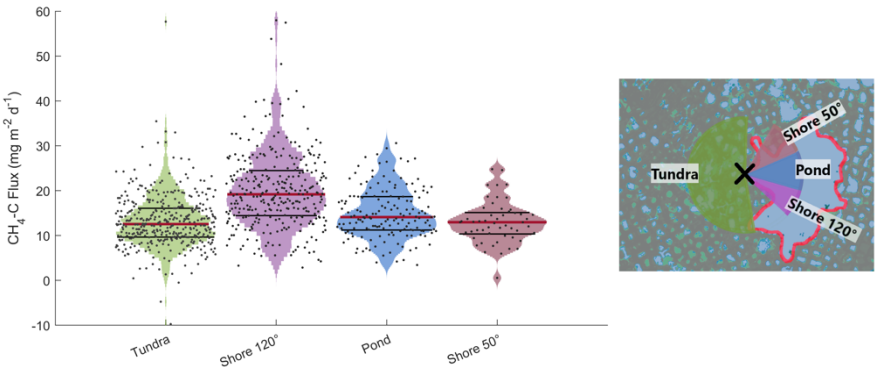

Figure 6. Violin plots of observed CH_4 emissions at the EC tower separated into four different wind direction classes. A violin plot shows the distribution of measurements along the y-axis - the width of the curves expresses the density of data points at each y-value. Medians of CH_4 emission distributions are shown as red lines, and 75th & 25th percentile are shown as black lines. On the right, the wind sectors with the eddy covariance tower in the center (black cross) are shown.

l. 213-214. to the mat&methods

Since we added the paragraph on CH_4 after line 188, we adapt l. 213-214 as follows:

To further investigate the peak at *shore*$_{120°}$, we compare the CH_4 emissions from the different wind sectors…

l. 217-221> belongs to the discussion

We slightly altered the paragraph (see below) to fit into the discussion section and include it in line 283.

Notably, we tested a dependence of these higher fluxes on wind speed and temperature. We expect high wind speeds to enhance turbulent mixing of the water column and diffusive CH_4 outgassing at the water-atmosphere interface. High wind speeds are also associated with pressure pumping, which potentially fosters ebullition of CH_4. Peak temperatures, on the other hand, can lead to peak CH_4 production and emissions due to enhanced biological activity. However, the high emissions from *shore*$_{120°}$ do not coincide with meteorological conditions which would especially favor high emissions.

l. 222-226. belongs to the mat&met

Thank you for this helpful comment. We moved the paragraph to the new method subsection "CH_4 Permutation Test" and referred to this paragraph in the result section.

l. 243. And CH4?

Due to the strong variability of the CH_4 fluxes and the lack of a well-tested model for tundra or water CH_4 fluxes, we could not extract the fluxes from the individual landcover types for CH_4. This extraction is a prerequisite for the upscaling. Thus, the upscaling was only conducted for CO_2. To highlight this at this point in the manuscript we added the following sentence after line 246:

As we have no estimates for the CH_4 fluxes from the landcover types *tundra* and *pond*, we only upscale CO_2.

Fig. 6. please, explain how to interpret the violin plot in terms of distribution along the x-axis?

Thank you for this suggestion. We added to following text at the end of Fig. 4 and 6:

A violin plot shows the distribution of measurements along the y-axis - the width of the curves expresses the density of data points at each y-value.

I would expect similar spatial analysis for CO2 and CH4. At least, both method descriptions should appear in the mat & met.

By adding two paragraphs on CH_4 in the method section (<u>CH_4 Flux Partitioning</u> and <u>CH_4 Permutation Test)</u> and by clarifying why we do not upscale the CO_2 fluxes, we hope that this comment is already covered. We would like to stress here that the spatial and temporal patterns of the two gasses are so different that we do not think a similar analysis would give meaningful results. We hope that adding the method descriptions is an acceptable alternative to the reviewer.

l. 267> that's a good point note. What about differences among the ponds/lakes? Vegetation or not, sediment quality, origin i.e., glacial vs thaw pond etc.

Thank you for this helpful remark. Yes, Abnizova et al. (2012) did not measure the merged polygonal pond which we focus on, we extend the discussion focusing on the pond characteristics as follow in line 270:

Abnizova et al. (2012) measured smaller thermokarst ponds, as opposed to the larger merged polygonal pond we focus on. While this might explain the deviations, there are also thermokarst ponds highly similar to the ones in Abnizova et al. (2012) in the footprint of the EC tower in this study. If those ponds would emit CO$_2$ in the quantities suggested by Abnizova et al. (2012), we would expect to see their signal more clearly in our measurements.

l. 303. One could carry out a measurement campaign in fine spatial resolution applying funnels and/or chambers to capture ebullition fluxes

Thank you for the suggestion, we added these possibilities. Please see below for the adjusted text.

So, a future visual inspection of trapped CH_4 bubbles in the ice column during wintertime, as proposed in Vonk et al. (2015), could reveal more information about the cause of the higher CH_4 emission from $shore_{120°}$, as could funnel or chamber measurements with high spatial coverage.

l. 309. Maybe not to automatically expect smaller or higher emissions from one or another and one should also consider variability in amounts of available substrates and temperature among the different habitats

Thank you for this suggestion. We clarify the reasons for the different expectations in the following way.

Considering the first part of your suggestion, we now base our expectations additionally on a study from Abisko, Sweden. We changed the text as follows:

However, substrate availability and temperature dynamics differ substantially. Additionally, in dense soils, methane diffuses through upper soil layers and can oxidize before reaching the surface. In contrast, methane emitted in ponds can reach the surface quickly through ebullition or higher plant-mediated transport in addition to diffusion. Therefore, we expect bigger differences between CH_4 emissions from the pond and the tundra, more similar to the differences detected in a subarctic lake and fen (Jammet et al., 2017).

l. 324. you could emphasis here the fact that you found a hotspot feature and recommend spatially representative measurement and mapping. In this case, near the pond shore.

Thank you for this suggestion. We edited the sentences as follows:

Instead, after finding a hotspot in CH_4 emission at the pond shore, we would like to highlight the need for spatially representative observation and mapping of CH_4 fluxes to better understand the variability of pond-CH_4 emissions.

l. 330. aquatic? do you mean landscape? included lakes and ponds in the landscape balance?

Thank you for this comment. After reading Abnizova et al. (2012) again, we replaced "aquatic" with "landscape" at the end of the sentence and hope that we cite the paper correctly by saying:

A similar approach by Abnizova et al. (2012) found a potential increase of 35 - 62 % in the estimate of CO2 emission from the Lena River Delta when including small ponds and lakes into the landscape CO2 emission.

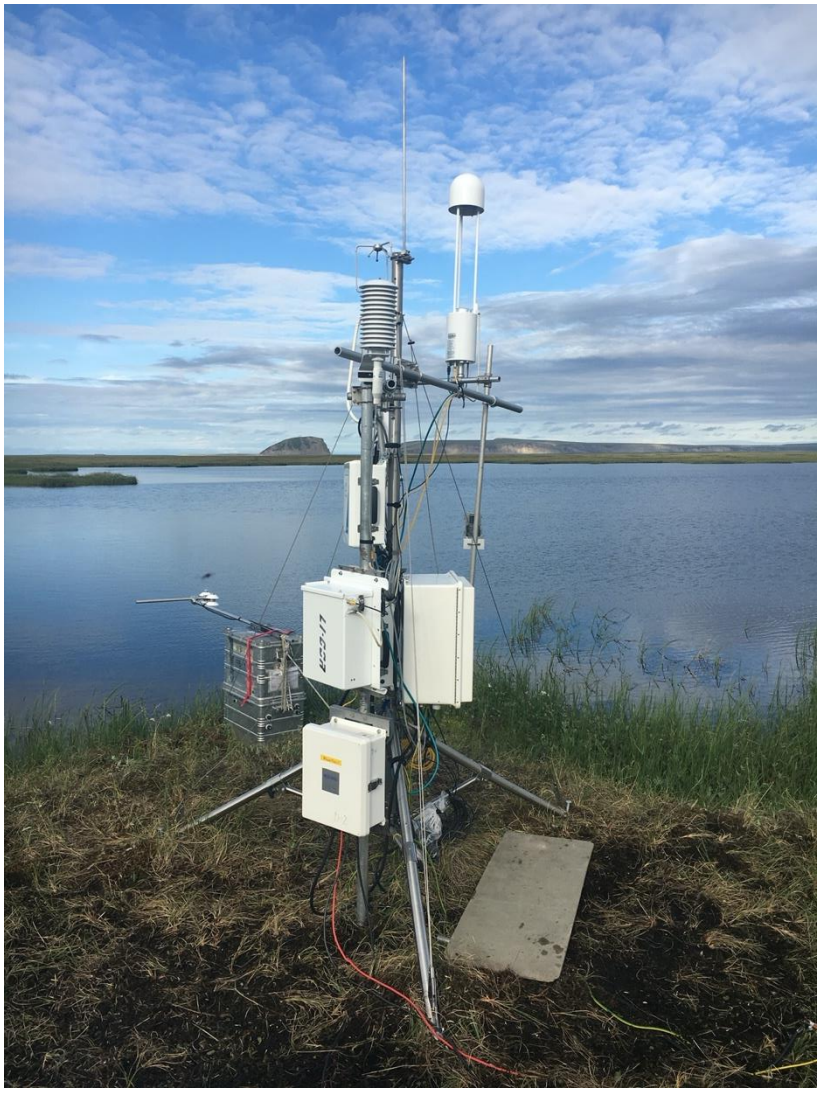

Figure A1. Picture of the eddy covariance tower with the merged polygonal pond in the background. Picture taken on 11 July 2019 by Zoé Rehder.

Literature

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