~~Small waterbodies reduce the carbon sink~~ Not accounting for thermokarst ponds leads to overestimation of ~~a polygonal~~ tundra ~~landscape~~carbon uptake

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Abstract. Arctic permafrost landscapes have functioned as a global carbon sink for millennia. These landscapes are very heterogeneous, and the omnipresent ~~waterbodies~~ water bodies are a carbon source within them. Yet, only a few studies focus on the impact of these ~~waterbodies~~ water bodies on the landscape carbon budget. We ~~compare carbon~~ deepen our understanding of carbon emissions from thermokarst ponds and constrain their impact by comparing carbon dioxide and methane fluxes from ~~small waterbodies~~ these ponds to fluxes from the surrounding tundra~~using~~ . We use eddy covariance measurements from a tower located between a large pond and semi-terrestrial ~~vegetated~~ tundra.

When taking the open-water areas of ~~small waterbodies~~ thermokarst ponds into account, the carbon dioxide sink strength of the landscape ~~was~~ is reduced by 11%. ~~While open-water methane emissions were similar to the tundra emissions~~Open-water methane emissions are of similar magnitude as tundra emissions. However, some parts of the ~~studied~~ pond's shoreline ~~exhibited~~ exhibit much higher emissions~~, underlining~~ . This finding underlines the high spatial variability of methane emissions. We conclude that gas fluxes from ~~small waterbodies~~ thermokarst ponds can contribute significantly to the carbon budget of arctic tundra landscapes. Consequently, changes in arctic hydrology and the concomitant changes in the ~~waterbody~~ water body distribution may substantially impact the overall carbon budget of the Arctic.

1 Introduction

~~Waterbodies~~

Water bodies make up a significant part of the arctic lowlands with an areal coverage of about 17% ~~, (Muster et al., 2017)and considerably decrease the landscape~~ (Muster et al., 2017), and act as an important carbon source in a landscape that is otherwise a carbon sink (Kuhn et al., 2018). ~~The thaw of permafrost in~~ Permafrost thaw caused by the warming Arctic ~~is going to~~ will change the distribution of waterbodies (Andresen and Lougheed, 2015; Bring et al., 2016) and thus also their contribution to the landscape-carbon budget (Kuhn et al., 2018). However, data on greenhouse-gas ~~emission from arctic waterbodies~~ emissions from arctic water bodies are still sparse in space and time, especially data with a high temporal resolution and ~~in~~ from non-Yedoma regions (Vonk et al., 2015).

Our study site, in the Lena River Delta, Siberia, is located on an island mostly covered by non-Yedoma polygonal tundra (Fig. 1). This landscape features many ponds~~(~~, which are defined here by an area $< 8 \cdot 10^4$ m^2, Ramsar Convention Secretariat (2016); Rehder et al. (2021)~~), as opposed to larger lakes, and in~~ . In our area of interest, ponds cover about as much area as lakes (Abnizova et al., 2012; Muster et al., 2012). 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 big as one polygon, but when several polygons are inundated, larger shallow water bodies form, which we call merged polygonal ponds (Rehder et al., 2021). Ponds emit more greenhouse gases per area than lakes (Holgerson and Raymond, 2016; Wik et al., 2016)~~, thus,~~ . Thus, in our study area, they have a higher potential than lakes to ~~reduce~~ counterbalance the carbon sink function of the surrounding tundra (McGuire et al., 2012; Jammet et al., 2017; Kuhn et al., 2018). To ~~estimate~~ better understand the impact of ponds on the landscape carbon flux, we compare ~~landscape~~ carbon dioxide (CO_2) and methane (CH_4) fluxes from the open-water area of ponds to ~~the more commonly reported~~ fluxes from the semi-terrestrial tundra~~(defined here~~ , which we define as wet and dry tundra~~as well as overgrown water)~~, and overgrown water.

~~Different~~ The main driving geophysical and biochemical processes ~~drive pond emissions of~~ differ between CO_2 and ~~of~~ CH_4 ~~. Aquatic CO_2 production is dominated by the~~ emissions. On the one hand, microbial decomposition of dissolved organic carbon, which is introduced laterally into the aquatic system through rain and ~~melt water (Neff and Asner, 2001)~~meltwater (Neff and Asner, 2001), dominates aquatic CO_2 production. When supersaturated with dissolved CO_2, ponds emit CO_2 to the atmosphere through diffusion. While photosynthetic CO_2 uptake has been observed in some clear arctic ~~waterbodies~~ water bodies (Squires and Lesack, 2003), most arctic ~~waterbodies~~ water bodies are net CO_2 sources (Kuhn et al., 2018). Estimates range from emissions close to zero (0.028 g m^2 d^{-1} by Treat et al. (2018), or 0.059 g m^2 d^{-1} by Jammet et al. (2017)) to substantial CO_2-C emissions (1.4 – 2.2 g m^2 d^{-1} by Abnizova et al. (2012)).

On the other hand, CH_4 emissions ~~have been found to~~ vary even more~~(~~, sometimes by up to five orders of magnitude within just one site: 0.5 – 6432 mg m^2 d^{-1}, Bouchard et al. (2015)~~). In contrast to CO_2, most~~ . CH_4 ~~originates in the~~ is mostly produced in sub-aquatic soils ~~. It is emitted from waterbodies not only through diffusionbut also through~~ and anoxic bottom waters (Conrad, 1999; Hedderich and Whitman, 2006; Borrel et al., 2011). 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 water bodies (Günthel et al., 2020) and is still under debate (Encinas Fernández et al., 2016; Peeters et al., 2019). Note that during methanogenesis, CO_2 is also formed as a byproduct (Hedderich and Whitman, 2006). CH_4 is then emitted from water bodies through diffusion, ebullition (sudden release of bubbles), and plant-mediated transport~~, often leading~~ . These three pathways lead to high spatial variability between ~~waterbodies~~ water bodies and within one ~~waterbody (Sepulveda-Jauregui et al., 2015; Jansen et al., 2~~ ~~. Local seep-ebullition events can cause~~ water body (Sepulveda-Jauregui et al., 2015; Jansen et al., 2019). Especially local seep ebullition causes high spatial variance of CH_4 emissions within one ~~waterbody~~ water body when it occurs (Walter et al., 2006).

Varying coverage and composition of vascular plants ~~in~~ within the shallow parts of a ~~waterbody~~ water body can also increase CH_4 variability ~~through plant-mediated transport~~ because each plant species has its specific efficiency in transporting CH_4 (Knoblauch et al., 2015; Andresen et al., 2017).

To study ~~both~~ spatial and temporal patterns, we analyze land-atmosphere CO_2 and CH_4 flux observations from an ~~eddy covariance~~ eddy-covariance (EC) tower ~~located~~ on Samoylov Island, Lena River Delta, Russia. We set the EC tower up within the polygonal tundra and next to a merged polygonal pond for two months in summer 2019. ~~A merged polygonal pond is a larger pond which formed through the subsidence of several polygons.~~ The polygonal structures are still clearly visible along the shore and ~~under water, and these ponds tend to be shallow for their size~~ underwater, and the pond is mostly shallow (Rehder et al., 2021). Due to the tower's position, fluxes from the merged polygonal pond are the dominant source of the observed EC fluxes under easterly winds. The observed EC fluxes are dominated by ~~vegetated~~ semi-terrestrial polygonal tundra with only a low ~~fraction from polygonal-center~~ influence from small thermokarst ponds from the other wind directions. We aim to deepen our understanding of carbon emissions from thermokarst ponds and constrain their impact on the landscape carbon balance. To this end, we (1) compare the ~~waterbody~~ water body and tundra fluxes ~~with a focus~~ focusing on temporal and spatial patterns, and we (2) investigate the influence of the merged polygonal pond on the landscape carbon balance.

2 Methods

2.1 Study ~~Site~~site

~~The study site~~ Samoylov Island (72°22'N, 126°28'E) ~~is located~~ lies in the southern part of the Lena River Delta (~~Figure~~ Fig. 1, b). It has a size of about ~~5~~ five km^2 and consists of two geomorphologically different ~~parts~~units. The western part ($\sim$2 km^2) is a floodplain ~~and regularly flooded during the annual springflood~~annually flooded in spring. The eastern part ($\sim$3 km^2), a late-Holocene river terrace, is characterized by polygonal tundra. The partially degraded polygonal tundra at this study site ~~shows~~ features a high spatial heterogeneity within a few meters. Dry and wet vegetated parts are interspersed with small and large thermokarst ponds (<1 m^2 – >10000 m^2) and with large thermokarst lakes (up to 0.05 km^2, Boike et al. (2015a); Kartoziia (2019)). The island is surrounded by ~~partially and regularly flooded branches of~~ the Lena River and sandy floodplains, creating more spatial heterogeneity on a larger scale.

We focus on a merged polygonal pond (~~Figure~~ Fig. 1, d~~), which is located~~ , and A1) in the eastern part of the island. ~~The~~ This merged polygonal pond ~~in our study~~ has a size of 0.024 km^2 with a maximum depth of 3.4 meters and a mean depth of 1.2 meters (Rehder et al., 2021; Boike et al., 2015a). On an aerial image, the polygonal structures are still clearly visible under the water surface (Boike et al., 2015c). The vegetated shoreline of this merged polygonal pond is dominated by *Carex aquatilis* interspersed with *Carex chordorrhiza*, *Potentilla palustris* and *Aulacomnium spp.*. ~~Some~~ These plants grow in the water ~~of the pond~~ close to the shore ~~. The~~ while the deeper parts of the pond are ~~vegetation free~~vegetation-free.

2.2 Instruments

We ~~measured~~ measure gas fluxes using an eddy covariance (EC) tower between July 11 and September 10, 2019. The EC tower ~~was~~ is located on the eastern part of Samoylov Island, directly at the western shore of the merged polygonal pond (~~Figure~~ Fig. 1, d). The EC instruments ~~were~~ are mounted on a tripod at the height of 2.25 meters ~~. The tower was equipped with a closed-path~~ (Fig. A1). The tower is equipped with an enclosed-path CO_2/H_2O sensor (LI-7200, LI-COR Biosciences, USA), an open-path CH_4 sensor (LI-7700, LI-COR Biosciences, USA), and a 3D-ultrasonic anemometer (R3-50, Gill Instruments Limited, UK). All instruments ~~had~~ have a sampling rate of 20 Hz.

~~Additional meteorological data for Samoylov Island was provided by Boike et al. (2019). We also installed~~ We also install radiation-shielded temperature and humidity sensors at the EC tower (HMP 155, Vaisala, Finland) and ~~used~~ use data from a photosynthetically active radiation (PAR) sensor mounted at a tower approximately 500 meters to the west (SKP 215, Skye Instruments, UK).

Additional meteorological data for Samoylov Island is provided by Boike et al. (2019).

2.3 Data ~~Processing~~processing

We perform the raw data processing and computation of half-hourly fluxes for open-path and ~~closed-path~~ enclosed-path fluxes using *EddyPro 7.0.6* (LI-COR, 2019). Raw data screening includes spike detection and removal according to Vickers and Mahrt (1997) (1% maximum accepted spikes and a maximum of ~~3~~ three consecutive outliners). Additionally, we apply statistical tests for raw data screening, including tests for amplitude resolution, skewness and kurtosis, discontinuities, angle of attack, and horizontal winds steadiness. All parameters of these tests are set to *EddyPro* default values. We rotate the wind-speed axis to a zero-mean vertical wind speed using the "double rotation"-method by Kaimal and Finnigan (1994). We apply linear detrending following Gash and Culf (1996) to the raw data ~~prior to the flux calculation~~before flux calculations. We compensate time lags by automatic time-lag optimization using a time-lag-assessment file from a previous EddyPro run. In this previous time-lag assessment, the time lags for all gases are detected by covariance maximization (Fan et al., 1990) resulting in time lags ~~of~~ between 0 – 0.4 s for CO_2 and -0.5 – +0.5 s for CH_4. For H_2O, the time lag is humidity-dependent and is calculated for ten humidity classes. We compensate for air-density fluctuations due to thermal expansion/contraction and varying water-vapor concentrations following Webb et al. (1980). This correction ~~is only applied to~~ depends on accurate measurements of the latent and sensible heat flux and is applied to the open-path data ~~; for closed-path~~ of the LI-7700. Especially for the LI-7700, the correction term can be larger than the flux itself, but the correction is derived from the underlying physical equations. By using *EddyPro*, which uses an up-to-date implementation of the correction, and by using well-calibrated instruments, we are certain to receive accurate CH_4 flux estimations from the LI-7700. For enclosed-path data, we perform a sample-by-sample conversion into ~~mixing-ratios~~ mixing ratios to account for air-density fluctuations (Ibrom et al., 2007b; Burba et al., 2012). Flux losses occur in the low- and high-frequency spectral range due to different filtering effects. In the low-frequency range, we compensate flux losses following Moncrieff et al. (2004) and in the high-frequency range following Fratini et al. (2012). For applying the latter method, a spectral assessment file is created using the method by Ibrom et al. (2007a). The spectral assessment results

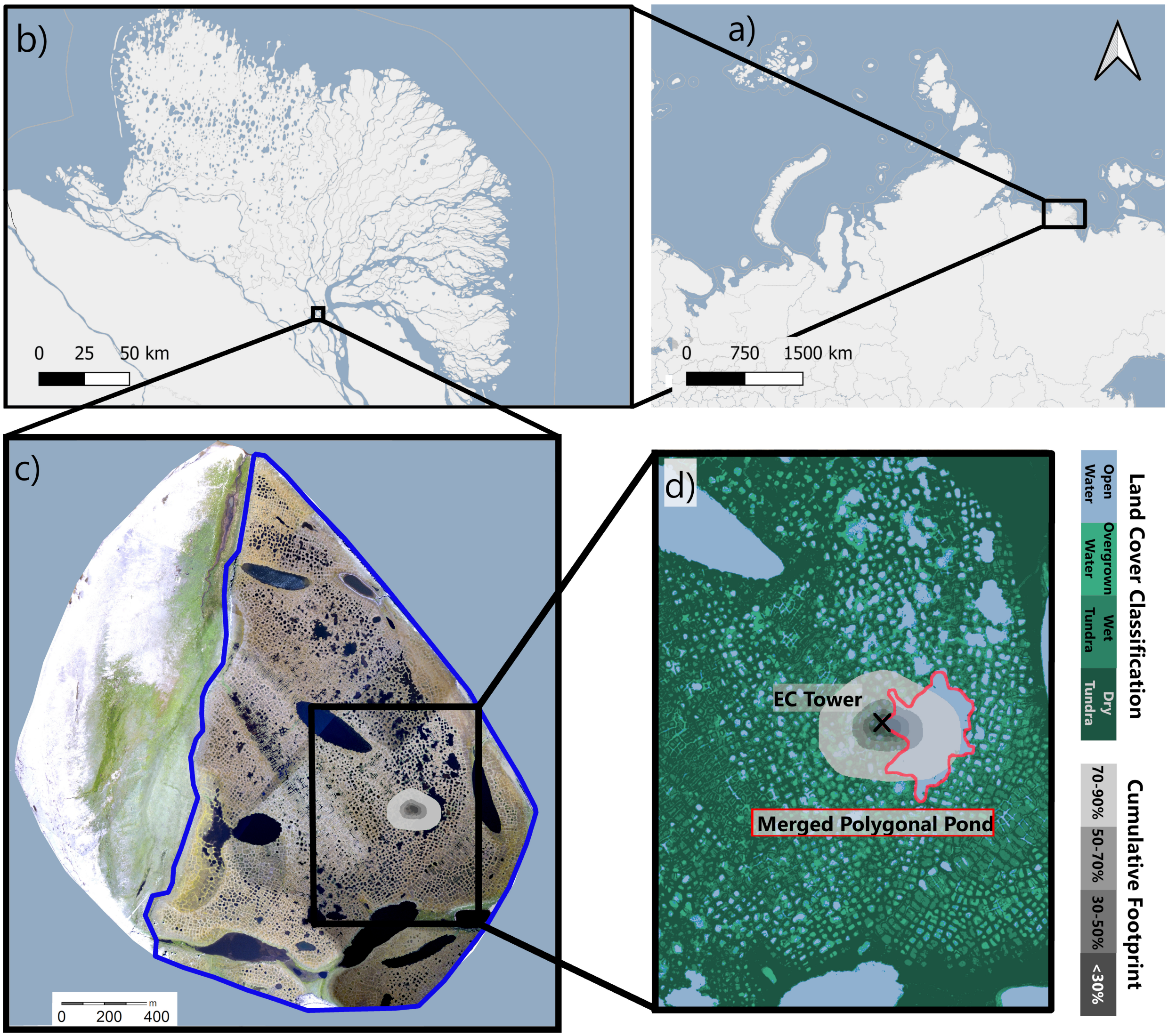

Figure 1. Study site with an overview of Russia (a), the Lena River Delta (b), Samoylov Island with the surrounding Lena River in blue (c), and a close-up look at the study site (d). The EC tower is marked as a black cross with the cumulative footprint (see section 2.4.2) in gray shades surrounding the EC tower. The outline of the land cover classification from section 2.4.1 is shown in a blue line (c). In (d), the detailed land cover classification is shown in blue (open water) and green shades (dark green: dry tundra, medium green: wet tundra, and light green: overgrown water). The merged polygonal pond studied here is outlined in red. Map data from © OpenStreetMap contributors 2020, distributed under the Open Data Commons Open Database License (ODbL) v1.0 (a & b) and modified after Boike et al. (2012) (c & d).

in cut-off frequencies of 3.05 Hz and 1.67 Hz for CO_2 and CH_4, respectively. For H_2O, we find a humidity-dependent cut-off frequency between 1.25 Hz (RH 5 - 45%) and 0.21 Hz (RH 75 - 95%). We perform a quality check of each flux interval on each half-hourly flux following the 0-1-2 system by Mauder and Foken (2004). In this quality check, flux intervals with the lowest quality receive the flag "2" and are excluded from further analysis.

2.4 Data Analysisanalysis

2.4.1 Land Cover Classificationcover classification

The land cover classification covers the late-Holocene river terrace of Samoylov Island(Siberia, Russia). It is based on high-resolution near-infrared (NIR) orthomosaic aerial imagery obtained in the summer of 2008 (Boike et al., 2015b). We use a subset of the existing classification by Muster et al. (2012) as a training dataset to perform a semi-supervised land cover classification using the *maximum likelihood algorithm* in ArcMap Version 10.8 (ESRI Inc, USA). We then apply the ArcMap *majority filter* tool to the new classification. The land cover classification has a resolution of 0.17 m x 0.17 m, it is projected onto WGS 1984 UTM Zone 52N and the classes include *open water*, *overgrown water*, *dry tundra*, and *wet tundra*, as defined by Muster et al. (2012).

2.4.2 Footprint Modelmodel

The tower location and sensor height are crucial parameters in the deployment of deploying an EC measurement tower. A lower measurement height results in a smaller footprint. The footprint describes the source area of the flux from the surrounding landscape. With our sensors installed at the height of 2.25 m next to the merged polygonal pond, we expect to observe substantial flux signals from the adjacent waterbody water body as well as from the surrounding polygonal tundra. Each land cover type's contribution to the flux signal depends on the wind direction and turbulence in the atmospheric boundary layer. We implement the analytical footprint model by Kormann and Meixner (2001) in Matlab 2019b (MATLAB, 2019)and . We combine the footprint model with land cover classification data described in section 2.4.1 to estimate the contribution of each land cover type to each flux signal (hereinafter from now on referred to as the weighted footprint fraction). The model accounts for the stratification of the atmospheric boundary layer and requires a height-independent crosswind distribution and horizontal homogeneity of the surface. The input data require the requires stationarity of atmospheric conditions during the flux interval intervals of 30 minutes. We derive the vertical power-law profiles for the eddy diffusivity and the wind speed for each 30-minute flux interval depending on the atmospheric stratification (equation 6 in Kormann and Meixner (2001)). We use an analytical approach to find the closest Monin-Obukhov (M-O) similarity profile (equation 36 in Kormann and Meixner (2001)). Next, we calculate a two-dimensional probability density function of the source area for each flux interval (from equation (from equations 9 and 21 in Kormann and Meixner (2001))and . We combine each probability density function with the land cover classification of the river terrace of Samoylov Island, with its four land cover types (see section 2.4.1). The footprint model's resolution resolution of the footprint model is set to the land cover classification resolution of 0.17 m x 0.17 m. Hence, for each grid cell within the source area, we can estimate the probability of the fraction of flux originating from this grid cell for how much a given grid cell contributes to each 30-min intervalflux. We also know the each grid cell's dominant land cover type in each grid cell from the land cover classification. We combine both information for each grid cell and calculate the sum of the fraction fluxes within the source area for each of the four land-cover types (*dry tundra*, *wet tundra*, *overgrown water*, and *open water*) and obtain the contribution of each land cover type to each 30-minute flux ($a_{dry\ tundra}$, $a_{wet\ tundra}$, $a_{overgrown\ water}$, and $a_{open\ water}$). We refer to this contribution of each land cover type as the *weighted footprint fraction*. We combine the contributions of the *dry tundra*, *wet tundra*, and *overgrown water* to a single land cover class for the semi-terrestrial tundra $a_{tundra} = a_{dry\ tundra} + a_{wet\ tundra} + a_{overgrown\ water}$.

We also take the sum of sum all 30-min two-dimensional probability density functions over the whole deployment time. This sum is referred to as the cumulative footprint . The cumulative footprint is shown as a (gray shaded area in Figure 1, c and dFig. 1, c–d). The light gray area's outer boundary represents the 90% isoline, and the light gray area's inner boundary is the 70% isoline of the cumulative footprint. This means that there is a probability of The 90% isoline means that it is likely that 10% that fluxes observed at the EC tower originate from areas of each observed flux signal originates from outside of the light gray area. Medium gray represents 50-70%, medium-dark gray 30-50%, and dark gray indicates that there is a probability of less than 30% that the observed flux each observed flux signal originates from within the marked area.

2.4.3 Bulk Model / Gap-Filling Gap-filling the CO_2 Flux flux

We use the bulk To gap-fill the net-ecosystem exchange of CO_2 (NEE) model by Runkle et al. (2013)fluxes of CO_2, we use the *bulk-NEE model* by Runkle et al. (2013). The model uses the total ecosystem respiration (TER) and the gross primary production (GPP) to gap-fill and partition our NEEflux observations. This model was specifically developed for modeling NEE, our target variable. The model is specifically designed to model NEE in arctic regionstaking into account : It takes impacts of the polar day into account. We estimate all model parameters for running 5-day periods to capture changing plant physiology during the measurement period.

NEE is partitioned into two components (equation 3): total ecosystem respiration TER (µmol m^{-2} s^{-1}, equation 1) and gross primary production GPP (µmol m^{-2} s^{-1}, equation 2). Parameters of both components are fit simultaneously. TER is modeled as an exponential function of air temperature T_{air}:

$$\text{TER} = R_{base} \cdot Q_{10}^{\frac{T_{air} - T_{ref}}{\gamma}} \tag{1}$$

where $T_{ref} = 15$ °C and $\gamma = 10$ °C are constant, independent parameters. R_{base} (µmol m^{-2} s^{-1}) describes the basal respiration at the reference temperature T_{ref} and Q_{10} (dimensionless) the sensitivity of ecosystem respiration to air temperature changes.

GPP is modeled as an a rectangular hyperbolic function of PAR (µmol m^{-2} s^{-1}):

$$\text{GPP} = -\frac{P_{max} \cdot \alpha \cdot \text{PAR}}{P_{max} + \alpha \cdot \text{PAR}} \tag{2}$$

where α (µmol µmol^{-1}) is the initial canopy quantum use efficiency (slope of the fitted curve at PAR$=0$) and P_{max} (µmol m^{-2} s^{-1}) the maximum canopy photosynthetic potential for PAR $\rightarrow \infty$.
We sum both components to estimate the modeled NEE $F_{CO_2,mod}$:

$$F_{CO_2,mod} = \text{TER} + \text{GPP}. \tag{3}$$

We split the datasets into a training (70%) and a validation (30%) data set to test model performance. ~~Additionally, we~~ In 38 5-day fitting periods, we find an R^2 above 0.9 between the model output and the validation set. Eighteen times, we get an R^2 between 0.8 – 0.9 and six times an R^2 below 0.7. The model performance indicates that the model works well overall. In the model input, we exclude CO_2 fluxes ~~from the direction~~ with an absolute value of more than 4 g m^{-2} d^{-1}. We additionally exclude CO_2 fluxes from the wind direction (WD) of the merged polygonal pond (30°< WD <150°) from the training dataset to obtain a dataset consisting of as much semi-terrestrial tundra as possible~~since we do not expect~~. We perform this step since we expect little to no photosynthetic activity in the ~~non-overgrown~~ open-water part of the merged polygonal pond.
We implement the ~~bulk model~~ *bulk model* in Matlab 2019b (MATLAB, 2019) using the *fit* function with the ~~fit-method~~ fitting method of *NonLinearLeastSquares*. We use the *coeffvalues*-function to estimate the four parameters and the *confint*-function to estimate their 95% confidence bounds. All partitioned fluxes are converted into CO_2-C fluxes in the unit g m^{-2} d^{-1} ~~prior to~~ before the data analysis.

2.4.4 ~~Aquatic~~ The open-water CO_2 ~~Flux~~flux

~~In a heterogeneous landscape, fluxes observed using the EC method contain~~ We want to extract fluxes from ponds and semi-terrestrial tundra to analyze the influence of ponds on a polygonal tundra landscape. However, due to the strong heterogeneity of the landscape and the relatively small size of the merged polygonal pond compared to the EC footprint, we measure a mixed signal from all wind directions. In other words, each flux measured with the EC method contains information from different land cover types. ~~In this study, we extract fluxes primarily related to ponds and tundra from the mixed signals. We then combine these estimated fluxes to analyze the influence of ponds on a polygonal tundra landscape~~Since we are interested in average tundra fluxes, we combine the landcover classes dry tundra, wet tundra, and overgrown water under the term *semi-terrestrial tundra*. In this way, we can compare two landcover classes, semi-terrestrial tundra and the open water from thermokarst ponds.

Similar approaches of analyzing heterogeneous eddy covariance fluxes in arctic environments have been conducted for CO_2 and CH_4 (e.g. Rößger et al., 2019a,b; Tuovinen et al., 2019). Rößger et al. (2019a,b) extracted CO_2 and CH_4 fluxes from two different land cover classes on a floodplain, and Tuovinen et al. (2019) separated CH_4 fluxes from nine individual land cover classes, including water, and combined them into four source classes (no separate class for water). All three studies have in common that they differentiate fluxes from different vegetation types. However, our method is dedicated to distinguishing between fluxes from tundra and water.

To estimate the CO_2 flux from the merged polygonal pond (F_{pond}), we first fit ~~a bulk model to data from which we exclude~~ the *bulk model* to data excluding fluxes from the direction of the merged polygonal pond (thus exclude fluxes ~~>~~from 30~~° &~~

~~>~~°< WD <150~~° wind direction). This modeled~~ °, as described in section 2.4.3). With this bulk model, we gap-fill the CO_2 flux, and the gap-filled CO_2 flux ($F_{modeled,mix}$) represents the ~~vegetated~~ semi-terrestrial tundra surrounding the EC tower, including small ponds to the north, west~~and south (with a weighted footprint fraction of open water of <30% in each flux signal) . In a second step, we make the assumption that individual contributions from different~~ , and south. Second, we assume that the total observed flux is a linear combination of the fluxes from the land cover types ~~to the observed flux scale linearly with their~~ weighted by their respective contribution to the footprint. Thus, we ~~can calculate~~ postulate that the observed CO_2 flux ($F_{obs,mix}$~~)~~ ~~as~~ , not gap-filled) is the sum of the individual land cover type fluxes ($F_{modeled,mix}$ and the merged polygonal pond F_{pond}) each multiplied with their weighted footprint fraction (a_{tundra} and a_{pond}~~, respectively, where~~), with $a_{open\ water} = a_{pond}$, $a_{tundra} = a_{sum} - a_{pond}$, and a_{sum} ~~being~~ is the sum over all land cover classes:

$$
\begin{aligned}
F_{obs,mix} &= a_{pond} \cdot F_{pond} + a_{tundra} \cdot F_{modeled,mix} \\
\Leftrightarrow F_{pond} &= \frac{F_{obs,mix} - a_{tundra} \cdot F_{modeled,mix}}{a_{pond}}
\end{aligned}
\tag{4}
$$

To improve data quality, we exclude 30-min ~~flux intervals~~ fluxes of F_{pond} when $a_{pond} < 50\%$. Then, we use the median of F_{pond} for further calculations, and we assume that all open water in the EC footprint emits the same amount of CO_2.

As mentioned above, the observed CO_2 flux from the north, west, and south ($F_{obs,mix}$) is still influenced by small thermokarst ponds. To analyze in detail the CO_2 flux from the ~~vegetated~~ semi-terrestrial tundra ($F_{\sout{modeled,veg}\,modeled,tundra}$), we subtract the previously estimated pond-CO_2 flux F_{pond} from the observed CO_2 flux $F_{obs,mix}$:

$$
F_{\sout{modeled,veg}\,modeled,tundra} = \frac{F_{obs,mix} - a_{pond} \cdot F_{pond}}{a_{tundra}} \tag{5}
$$

We then use this estimated CO_2 flux from the ~~vegetated tundra $F_{modeled,veg}$~~ semi-terrestrial tundra $F_{modeled,tundra}$ as the input variable for the ~~bulk model~~ *bulk model* to receive a gap-filled dataset of CO_2 flux from ~~vegetated~~ semi-terrestrial tundra.

2.4.5 ~~Up-scaled CO_2 flux~~

To evaluate the impact of ponds on the landscape CO_2 flux~~without the influence of ponds~~, we estimate a polygonal-tundra landscape-CO_2 flux (F~~$_{Landscape}$) including ponds~~ $_{landscape}$) by linearly combining ~~the two landscape forms (ponds and vegetated tundra):~~ ponds and semi-terrestrial tundra:

$$
F_{\sout{Landscape}\,landscape} = A_{pond} \cdot F_{pond} + A_{tundra} \cdot F_{\sout{tundra}\,modeled,tundra}
$$

where F_{pond} describes the CO_2 emission from the ~~merged polygonal pond~~ open-water areas of ponds (equation 4), ~~F_{tundra}~~ $F_{modeled,tundra}$ the modeled CO_2 flux from the ~~vegetated~~ semi-terrestrial tundra (equation 5), $A_{pond} = 0.07$ the coverage of open pond water on the whole river terrace of Samoylov Island (from the land cover classification, section 2.4.1) and $A_{tundra} = 1 - 0.07$ the coverage of other land cover types. We do ~~no~~ not account for (larger, deeper) thermokarst lakes in this up-scaling approach, as we expect different greenhouse gas ~~processes~~ emissions from these lakes and there are no lakes in our footprint. Thus, we scale the above numbers to $A_{tundra} + A_{pond} = 1$ which results in $A_{pond} = 0.076$ and $A_{tundra} = 0.924$.

2.4.5 CH_4 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. We focus on wind sectors instead of extracting the fluxes from the landcover types. We divide fluxes into the following wind sectors:

- *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°< WD <65°.
- *pond*: At least half of the footprint consists of open water, and the wind direction lies between 65°< WD <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°< WD <130°.

2.4.6 CH_4 permutation test

To evaluate whether the differences in medians between the four wind sectors are significant, we apply a permutation test (Edgington and Onghena, 2007). In this test, we randomly assign each 30-min flux to one of two groups and calculate both groups' median and their differences. Using the four wind sectors, we do six tests in total. After repeating this step 10000 times, we plot the resulting differences in medians in a histogram and perform a one-sample t-test to evaluate whether the observed difference in medians differs significantly ($p<0.01$) from the randomly generated differences.

3 Results

3.1 Meteorological ~~Conditions~~conditions

During the measurement period between 11 July and 10 September 2019, half-hourly air temperatures ~~ranged~~ range from -0.5 °C to 27.6 °C with a mean temperature of 8.7 °C (~~Figure~~ Fig. A2, a). The maximum wind speed measured on the EC tower at 2.25 m height ~~was~~ is 8.9 m s^{-1} (~~Figure~~ Fig. A2, b). Photosynthetically active radiation (PAR) ~~reached~~ reaches values of up to 1419 µmol m^{-2} s^{-1} with decreasing maximum values during the measurement period (~~Figure~~ Fig. A2, c). 28 cloudy days are ~~clearly~~ visible as days with low PAR-values (below ~500 µmol m^{-2} s^{-1}) throughout the measurement period.

3.2 CO_2 ~~Fluxes~~fluxes

~~Figure 2 shows the~~ When inspecting the relation between observed CO_2 fluxes ~~plotted against the wind direction . The~~ and wind direction (Fig. 2), we find that the CO_2 flux exhibits a high temporal variability between positive and negative CO_2 fluxes from most wind directions. In the wind ~~direction~~ sector between 60° – 120°, the flux is dominated by the merged polygonal pond. The ~~flux signal from this sector has~~ CO_2-C fluxes from this pond sector show a smaller variability (mean of 0.06 g m^{-2} d^{-1} with a standard deviation of ~~0.073~~ 0.28 g m^{-2} d^{-1}) than the fluxes from ~~the other wind direction sectors (~~all other wind

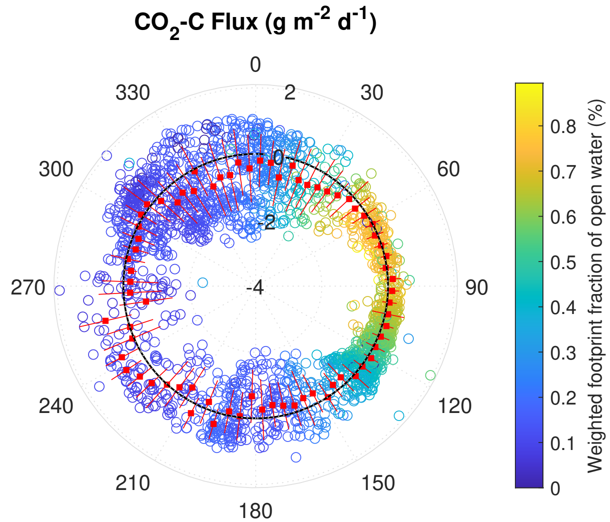

Figure 2. Polar plot of observed 30-min CO_2-C flux with respect to the wind direction at the EC tower. Negative values (inside of the dotted black line) represent CO_2 uptake, positive values (outside of the dotted black line) CO_2 emission. The values -4, -2, 0, and 2 indicate the magnitude of the CO_2-C flux in g m^{-2} d^{-1}. The color represents the percentage of open water weighted footprint fraction in each 30-minute flux~~interval~~. The red boxes indicate the mean CO_2 flux of 5° wind direction intervals during the 2-months observation period (red lines indicate the first standard deviation).

directions (mean of -0.17 g m^{-2} d^{-1} with a standard deviation of ~~0.56~~ 0.77 g m^{-2} d^{-1}). Additionally, we observe a lower respiration rate from the pond than from the semi-terrestrial tundra. ~~Figure~~ Fig. 3 shows the observed night-time CO_2 fluxes plotted against the respective weighted footprint fraction of ~~open-water in each flux when only considering night-time fluxes (~~open water. We define nighttime as PAR<20 µmol m^{-2} s^{-1} ~~, thus only respiration). The~~ and expect only respiration and no photosynthesis during these times. We find that the fluxes decrease with an increasing open-water contribution. Thus, the strength of respiration shows a dependence on the open-water contribution. We also find that low air temperatures are mostly associated with low respiration rates.

Another part of the CO_2 variability stems from the diurnal cycle. We compare the diurnal cycle of the CO_2 fluxes from the merged polygonal pond (estimated following equation 4) and the semi-terrestrial tundra (~~equation 5) in Figure 4. We~~ Eq. 5, Fig. 4), and we see a less pronounced diurnal CO_2 cycle from the direction of the merged polygonal pond (blue) compared to the diurnal CO_2 cycle from the tundra (green). All data from the merged polygonal pond combined (F_{pond} in Eq. 4) result in a CO_2-C flux of $\mathbf{0.13}\,^{\mathbf{0.24}}_{\mathbf{0.00}}$ g m^{-2} d^{-1} (Median $^{75\%\ \text{Percentile}}_{25\%\ \text{Percentile}}$).

3.3 CH_4 ~~Fluxes~~fluxes

~~Figure 5 shows the~~ When plotting observed CH_4 fluxes ~~plotted against the wind direction . The~~ against wind direction (Fig. 5), we see that the CH_4 emissions peak at $\sim 120°$, where fluxes from ~~a~~ one shoreline of the merged polygonal pond contribute

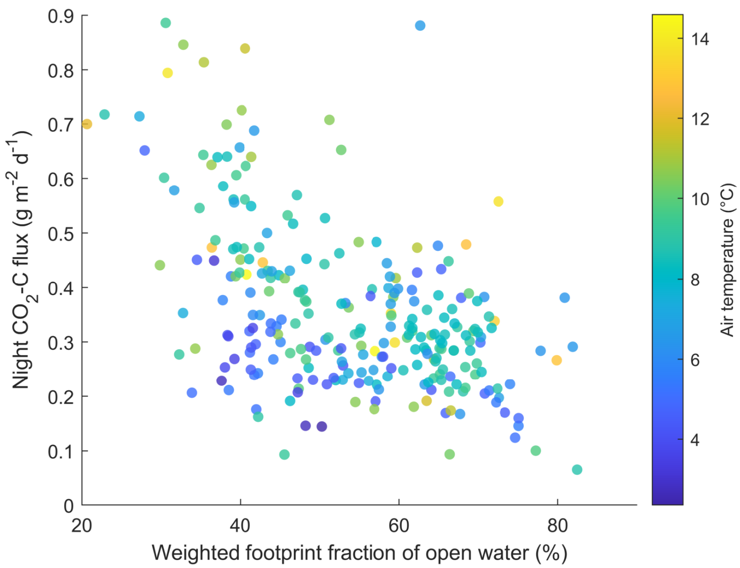

Figure 3. Scatter plot of observed CO_2 fluxes against the weighted footprint fraction of open water in each 30-minute flux interval with temperature as color. Only flux intervals fluxes at night time nighttime (PAR<20 µmol m^{-2} s^{-1}) are shown.

to the observed flux (see Figure Fig. 1 d, hereinafter from now on *Shoreshore*$_{120°}$). We do not observe a similar peak of CH_4 emissions in the direction of the second shoreline towards $\sim 50°$ (*Shoreshore*$_{50°}$). These peaks did not correlate with any of the four weighted footprint fractionsland-cover classes.

To further investigate the peak at *Shoreshore*$_{120°}$ *we separate* , we compare the CH_4 emissions into four sectors depending on wind direction (from the different wind sectors (*Shoreshore*$_{120°}$, *Shoreshore*$_{50°}$, *pond* and *tundra*, see Figure 6section 2.4.5). We find the following fluxes from the wind direction sectors: $19.18\,^{24.47}_{14.26}$ mg m^{-2} d^{-1} (*Shoreshore*$_{120°}$), $12.96\,^{15.11}_{10.34}$ mg m^{-2} d^{-1} (*Shoreshore*$_{50°}$), $13.38\,^{15.92}_{10.55}$ $13.90\,^{18.46}_{11.02}$ mg m^{-2} d^{-1} (*pond*), and $12.55\,^{16.07}_{9.65}$ mg m^{-2} d^{-1} (*tundra*, $Median\,^{75\%Percentile}_{25\%Percentile}$). Fluxes from *Shoreshore*$_{120°}$ have a higher median than fluxes from the other three wind sectors (see Figure Fig. 6). High wind speeds enhance turbulent mixing of the water column and diffusive CH_4 outgassing at the water-atmosphere interphase. High wind speeds are also associated with stronger pressure pumping potentially fostering ebullition, and thereby

We investigated the impact of wind and air temperature on the CH_4 emission. Additionally, peak temperatures can also lead to peak CH_4 production and emissions. So, we investigated these confounding factors fluxes by excluding flux intervals with high wind speed (larger than 5 $\frac{m}{s}$ m s^{-1}) and high air temperature (larger than 12 °C).

To evaluate whether the differences in medians between the four wind sectors are significant, we apply a permutation test (Edgington and Onghena (2007), Figure A4 and A5). In this test, we randomly assign each 30-min flux signal to one of two groups, calculate the median of both groups and their difference. After repeating this step 10000 times, we plot the resulting differences in medians in a histogram and perform a one-sample t-test to evaluate whether the observed difference in medians

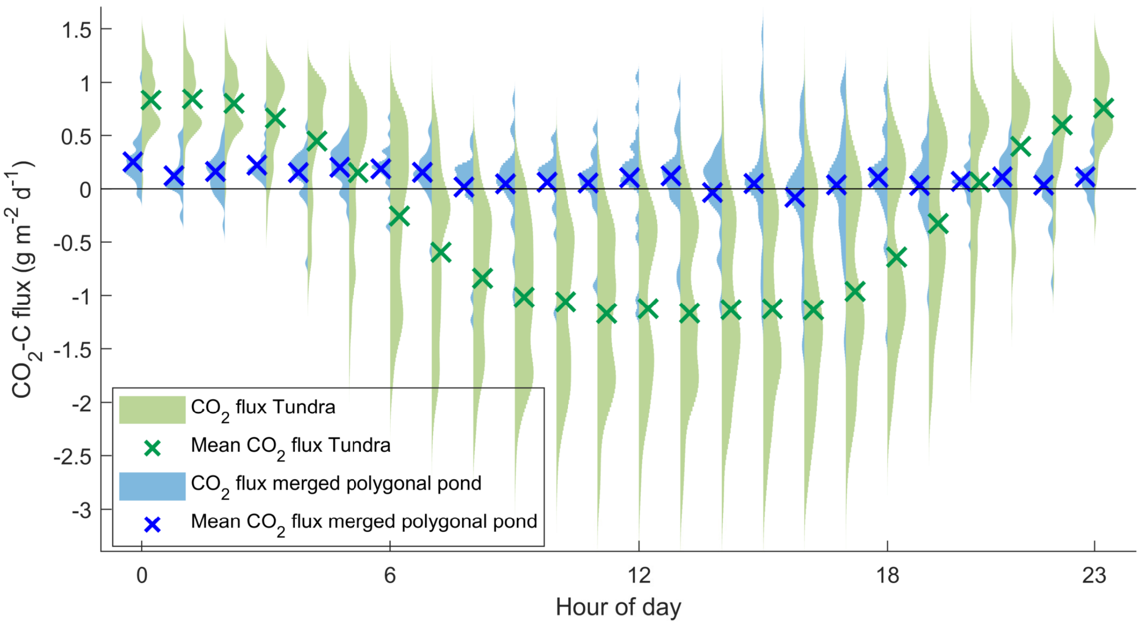

Figure 4. Diurnal cycle of modeled CO_2-C flux from the merged polygonal pond (blue, eq. 4) and the tundra (green, eq. 5) as violin plots for each half-hour flux~~interval~~. Blue and green crosses mark the mean CO_2-C flux during each half-hour flux~~interval~~. A violin plot shows the distribution of measurements along the y-axis – the width of the curves expresses the density of data points at each y-value.

~~differs significantly ($p<0.01$) from the randomly generated differences. In the randomization test we~~ In the randomization test (section 2.4.6), we find evidence for a significant difference between the CH_4 emission from ~~*Shore*~~*shore*$_{120^\circ}$ and the other three classes at low wind speeds (top row in ~~Figure~~ Fig. A4) and no significant difference between the CH_4 emission from the ~~other three classes (*Shore*$_{50^\circ}$,~~ classes *pond* ~~and~~ - *tundra* and *shore*$_{50^\circ}$ - *tundra*~~).~~. The difference between the classes *pond* and *shore*$_{50^\circ}$ is significant, however much smaller than the previously described differences (center graph in Fig. A4). Note that the CH_4 emissions from the pond and the tundra have a similar magnitude under moderate wind speed conditions. The results are very similar for moderate temperatures: We find evidence for a significant difference between the CH_4 emission from ~~*Shore*~~*shore*$_{120^\circ}$ ~~and~~ to the other three classes (top row in ~~Figure~~ Fig. A5). The differences in medians between the ~~pond and~~ *pond* and ~~*Shore*~~*shore*$_{50^\circ}$ ~~as well as between the pond and the tundra~~ and between the *pond* and *tundra* are significant. However, this difference is much smaller (second row in ~~Figure~~ Fig. A5).

In summary, we find ~~no meteorological parameter acting~~ that neither high wind speed nor high temperatures act as a driver for the high CH_4 emission from ~~*Shore*~~*shore*$_{120^\circ}$. ~~Note that the CH_4 emissions from the pond and the tundra have a similar magnitude under moderate wind speed conditions. When comparing the ratio of CH_4 emissions to~~

The ratio of CO_2~~emissions, we find that fluxes with an open-water weighted footprint fraction of more than 60% have a ratio of $CH_4/CO_2 = 0.057^{0.104}_{-0.049}$ (Median$^{75\%\ \mathrm{Percentile}}_{25\%\ \mathrm{Percentile}}$), while for fluxes intervals with less than 20% open-water contribution we~~

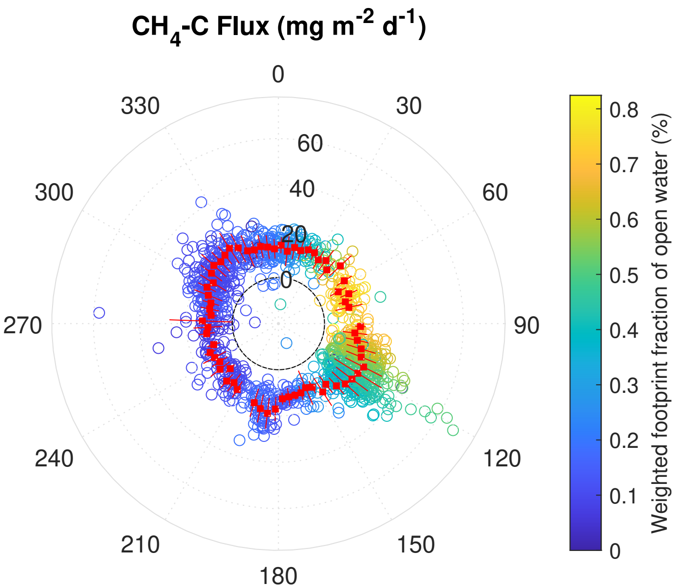

Figure 5. Polar plot of 30-minute observed CH_4-C flux with respect to the wind direction at the EC tower. Positive values outside of the dotted black line represent CH_4 emission, and inside of the line, CH_4 uptake during one half-hour period. The values 0, 20, 40, and 60 indicate the magnitude of the CH_4-C flux in mg m^{-2} d^{-1}. The color represents the percentage of open water weighted footprint fraction in each fluxinterval. The red boxes indicate the mean CH_4 flux of 5° wind direction intervals during the 2-months observation period (red lines indicate the first standard deviation).

observe a negative ratio (due to the negative CO_2 fluxes) with a larger spread of -C to CH_4/CO_2 = $-0.010^{0.021}_{-0.028}$ ($\text{Median}^{75\%\text{Percentile}}_{25\%\text{ Percentile}}$). The distributions of these two ratios are significantly different (Mann-Whitney-U test, $p < 0.01$). When considering only night-time fluxes (-C emissions at night (PAR<20 µmol m^{-2} s^{-1}) , the ratio of has a value of $CH_4/CO_2 = 0.060^{0.076}_{0.049}$ for fluxes with an open-water weighted footprint fraction of more than 60%is similar ($CH_4/CO_2 = 0.060^{0.076}_{0.049}$, $\text{Median}^{75\%\text{ Percentile}}_{25\%\text{ Percentile}}$), whereas ratio with less than 20% open-water contribution is now positive , whereas the ratio amounts to ($CH_4/CO_2 = 0.020^{0.024}_{0.015}$, $\text{Median}^{75\%\text{ Percentile}}_{25\%\text{ Percentile}}$) . The distributions of these two ratios are still significantly different (Mann-Whitney-U test, $p < 0.01$)for fluxes with an open-water weighted footprint fraction of less than 20%.

3.4 Upscaled CO_2 flux

We use the estimated aquatic open-water CO_2 flux from the merged polygonal pond and the modeled CO_2 flux from the semi-terrestrial tundra to linearly up-scale the CO_2 flux for the polygonal-tundra landscape polygonal tundra of Samoylov Island (excluding larger thermokarst lakes, the method described in section ??). 2.4.4). As we have no estimates for the CH_4 fluxes from the landcover types *tundra* and *pond*, we only upscale CO_2.

We estimate that the tundra landscape CO_2 uptake would decrease by is $\sim 11\%$ lower when including the CO_2 flux from ponds compared to a completely semi-terrestrial tundra without ponds. The modeled CO_2-C flux from the semi-terrestrial

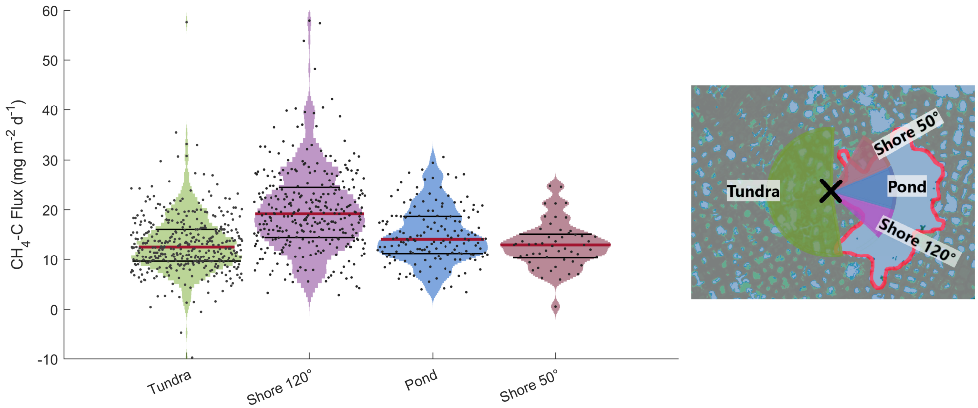

Figure 6. Violin plots of observed CH_4 emissions at the EC tower separated into four different wind direction classes. A violin plot shows the distribution of measurements along the y-axis - the width of the curves expresses the density of data points at each y-value. Medians of CH_4 emission distributions 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.

tundra (without consideration of pond fluxes) accumulated to -16.29 $\pm$ 0.43 g m^{-2} during the observation period (60.5 days). Separated into months, it amounts to -15.01 $\pm$ 0.26, -3.56 $\pm$ 0.33 and +2.35 $\pm$ 0.11 g m^{-2} in July (19.8 days), August (31 days), and September (9.7 days), respectively. When including the CO_2 flux from the merged polygonal pond as representative for all ponds on Samoylov island, the resulting estimate of the landscape CO_2 flux amounts to -14.47 $\pm$ 0.40 g m^{-2} (60.5 days) and ~~to~~ monthly fluxes of -13.75 $\pm$ 0.24, -2.99 $\pm$ 0.31, and +2.27 $\pm$ 0.10 g m^{-2} in July (19.8 days), August (31 days), and September (9.7 days), respectively. Thus, ~~in August, the estimate of~~ ponds have the largest impact on the landscape CO_2 ~~uptake is reduced most~~flux in August. In September, ~~the estimate of landscape emissions is decreased by~~ accounting for ponds leads to 3.5% ~~when including pond CO_2 emissions.~~ lower landscape emissions.

4 Discussion

4.1 CO_2 flux

Only a limited number of EC CO_2-flux studies from permafrost-affected ponds and lakes are available (studies with "EC" in ~~table~~ Tab. 1). Estimates of ~~aquatic~~ open-water EC CO_2-C flux range from 0.059 g m^{-2} d^{-1} (Jammet et al., 2017) over 0.11 g m^{-2} d^{-1} (Eugster et al., 2003) to 0.22 g m^{-2} d^{-1} (Jonsson et al., 2008). Our estimate of $0.12\,^{0.24}_{0.0014}$ g m^{-2} d^{-1} is~~therefore~~, therefore, well within the range of ~~aquatic~~ open-water CO_2-C fluxes observed with the EC method. Other studies using different methods report a wider range of ~~aquatic~~ open-water CO_2 fluxes in arctic regions. These fluxes range from a CO_2-C uptake (-0.14 g m^{-2} d^{-1}, Bouchard et al. (2015)) to substantial emissions of CO_2-C (up to 2.2 g m^{-2} d^{-1}, Abnizova et al. (2012)). A modeling study involving multiple lakes in north-eastern European Russia found close to zero emissions (0.028

Table 1. Daily mean water-atmosphere CO_2 & CH_4 fluxes from different study sites. TBL is the abbreviation for thin boundary layer model, EC for eddy covariance, CH for chamber measurement, MOD for modelled fluxes, STO for storage fluxes, and NEW for the method ~~proposed~~ used in this study. All fluxes are given ± standard deviation, except of fluxes from this study are given as Median $^{75\%\ \text{Percentile}}_{25\%\ \text{Percentile}}$.

Study	Location	Period/Time	Study Site	Method	CO_2-C ~~Flux~~ flux (g m^{-2} d^{-1})	CH_4-C ~~Flux~~ flux (mg m^{-2} d^{-1})
This study	Lena Delta,	11.07.–	merged polygonal pond	EC/NEW	$0.13^{0.24}_{0.00}$	
	Northern Siberia	10.09.2019	merged polygonal pond shore	EC	–	~~$13.38^{15.92}_{10.55}$~~ $14.10^{18.67}_{11.23}$
						$12.96^{15.11}_{10.34} - 19.18^{24.47}_{14.26}$
Abnizova	Lena Delta,	01.08.–	Samoylov Pond	TBL	1.50 – 2.20	
et al. (2012)	Northern Siberia	21.09.2008	Samoylov Lake	TBL	1.40 – 2.10	–
						–
Jammet et al. (2017)	Northern Sweden	2012 – 2013	Lake Villasjön	EC	0.059	13.42 ± 1.64
Jonsson et al.	Northern Sweden	17.06.–	Lake Merasjärvi	EC	0.22 ± 0.002	
(2008)		15.10.2005		TBL	0.30 ± 0.01	–
Eugster et al.	Alaska	27.07 –	Toolik Lake	EC	0.11 ± 0.033	
(2003)		31.07.1995		TBL	0.13 ± 0.003	–
				CH	0.37 ± 0.060	
Jansen et al.	Northern Sweden	Year round, 2010 –	Villasjön	CH	0.22 ± 0.047	14.04 ± 2.25
(2019)		2017	Inre Harrsjön		0.25 ± 0.05	10.39 ± 1.40
			Mellersta Harrsjön		0.73 ± 0.067	13.76 ± 2.81
Bouchard	NE Canada	July 2013 & 2014	Bylot Island, Polygon ponds	TBL	-0.14 – 0.74	0.50 – 6432
et al. (2015)			Lakes		-0.085 – 0.062	0.70 – 74.5
Sepulveda-	Alaska	June – July	8 Lakes, Yedoma	TBL & STO	0.60 ± 0.58	92.86 ± 35.72
Jauregui et al. (2015)		2011 & 2012	32 Lakes, Non-Yedoma		0.10 ± 0.10	16.80 ± 8.61
Treat et al. (2018)	Northeast European Russia	2006 – 2015	Multiple Lakes	MOD	0.028 ± 0.00011	0.84 ± 0.0
Sieczko et al. (2020)	Northern Sweden	July – August 2017	Lake Ljusvatterntjärn	CH	–	2.95 ± 0.75
Ducharme-Riel et al. (2015)	North-East Canada	Summer 2008	15 lakes	TBL	0.20 ± 0.093	–
Repo et al.	Western Siberia	03.07.–	MTlake	TBL	0.14 ± 0.11	
(2007)		06.09.2005	FTlake	TBL	0.41 ± 0.25	–
			MTpond	TBL	0.44 ± 0.25	
Lundin et al. (2013)	Northern Sweden	2009 (only ice-free season)	27 lakes	TBL	0.18 ± 0.11	–
Kling et al. (1992)	Alaska	1975 – 1989	25 lakes	TBL	0.25 ± 0.040	5.16 ± 0.96

g m^{-2} d^{-1}, Treat et al. (2018)). Perhaps the Our perhaps most striking finding is that our estimates of aquatic open-water CO_2 emissions are approx. 12-18 times smaller than previously reported for aquatic open-water CO_2 emissions at the same study site (Abnizova et al., 2012). One reason for the divergent results might be the different methods used. In Abnizova et al. (2012), the thin boundary layer model (TBL) after Liss and Slater (1974) has been used was applied to estimate CO_2 emissions from analyzed CO_2 concentrations measured in water samples. However, one other study found good agreement between the EC method and the TBL (Eugster et al., 2003), so we cannot conclusively explain . 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 emitted CO_2 in the quantities suggested by Abnizova et al. (2012), we would expect to see their signal more clearly in our measurements. Thus, we cannot conclusively resolve the differences.

Our approach of combining a footprint model with a land cover land-cover classification to extract fluxes from different land cover land-cover classes allows us to determine the pond CO_2 flux. We report an uncertainty range of the pond CO_2 flux; however, we can not cannot identify the full uncertainty of this flux in this novel approach due to the unknown uncertainty of the footprint analysis. Still, the pond CO_2 flux results are plausible and in the correct order of magnitude for two reasons. First, a reduced diurnal variability has been observed when the pond influences the flux signal (figure Fig. 4). This reduction indicates that the respiration rate from the pond is lower than the respiration rate from the semi-terrestrial tundra, where ample oxygen is available in the upper soil layer. Additionally, there is less photosynthesis since the ponds have a lower vegetation density than the tundra, there is less photosynthesis. Second, when focusing on night-time fluxesonly, when only respiration occurs, and no carbon uptakeis taken up, there is a decrease in CO_2 emission with an increasing weighted footprint fraction of open water (shown in figure Fig. 3), also indicating reduced decomposition in the pond. Overall, the lower emissions from the pond compared to the semi-terrestrial tundra are reasonable.

4.2 CH_4 flux

We observe large differences in CH_4 emission from different wind sectors. CH_4 emissions from *Shoreshore*$_{120°}$ are significantly higher than from *Shoreshore*$_{50°}$, *pond* or *tundra* , independently of meteorological conditions (see (section 3.3). Especially the difference between Notably, we tested the dependence of these higher fluxes on wind speed and air 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 the ebullition of CH_4. On the other hand, peak temperatures 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 of high wind speeds or high temperatures, which would especially favor high emissions. Thus, the difference between *Shoreshore*$_{120°}$ and *Shoreshore*$_{50°}$ is astounding since the shorelines share many characteristics. Both extend radially (in a straight line) from the EC tower (see figure Fig. 1), thus contribute contributing similarly to the EC flux. The underwater topography does not vary much between the two shorelines. Both shorelines have a water depth between a few centimeters and a few decimeters within meters away from the shore (see data from Boike et al. (2015a)). As previously described in section 2.1, both shorelines are dominated by *Carex* *aquatilis*, and from visual inspection~~we can not~~ , we cannot find differences in shoot density. We, therefore, assume that the vegetation type does not play a major role in explaining the differences between the CH_4 emission from ~~*Shore*~~*shore*$_{120°}$ and ~~from *Shore*~~*shore*$_{50°}$. We also examine the evolution of the shorelines at the merged polygonal pond to check whether erosion along the shoreline could drive the high CH_4 emissions. We compare a coarse image from 1965 (U.S. Geological Survey, EROS Center, 1965) with the current shoreline~~; yet, we can not~~ , yet we cannot identify signs of recent erosion. Also~~high resolution~~ , high-resolution aerial images of the pond from 2008 (Boike et al. (2015b), resolution > 0.33 m) and 2015 (Boike et al. (2015c), resolution > 0.33 m) show no signs of erosion. Thus, we exclude erosion as a driving factor of high CH_4 emissions.

We also consider the possibility that local ebullition of the pond could lead to high CH_4 emissions from ~~*Shore*~~*shore*$_{120°}$. We apply the method proposed by Iwata et al. (2018) to check for signs of ebullition events. This method uses the 20 Hz raw concentration of CH_4 to detect short-term peaks in CH_4 that originate from ebullition events. However, we ~~can not~~ cannot detect ebullition events in the 20 Hz raw data.

In summary, many causes, such as meteorological conditions (wind speed or temperature), vegetation type, coastal erosion, and intense ebullition events, can be excluded as driving factors. Therefore, the most likely cause of the higher CH_4 emissions from ~~*Shore*~~*shore*$_{120°}$ might be a small but steady seep ebullition hot spot close to this shoreline (such as ebullition class *Kotenok* in Walter et al. (2006)). Seep ebullition hot spots have been reported to occur heterogeneously in clusters in Alaskan lakes (Walter Anthony and Anthony, 2013). 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 the ~~*Shore*~~*shore*$_{120°}$, as could funnel or chamber measurements with high spatial coverage.

~~Excluding the high emissions from *Shore*$_{120°}$, the CH_4 emission from the~~ The merged polygonal pond ~~and the tundra surface have a very similar magnitude~~ emits CH_4 with a similar magnitude as the tundra surface under similar meteorological conditions ~~. In both landscape types, CH_4 is produced under anoxic conditions, but the emission pathways~~ and when excluding the high emissions from *shore*$_{120°}$. However, substrate availability and temperature dynamics differ substantially. ~~In~~ 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. ~~We expected~~ Therefore, we expect bigger differences between CH_4 emissions from the pond and the tundra~~due to the different emission pathways~~, more like the differences detected in a subarctic lake and fen (Jammet et al., 2017). Yet, ~~as shown in figure 6, c) and A4,~~ we see no significant difference in CH_4 emission from the open-water areas of the merged polygonal pond and the tundra surface ~~.~~ (Fig. 6 & A4).

Since many other ponds are smaller than the pond (making them unsuitable for studying with the EC method), and since smaller ponds tend to be stronger emitters (Holgerson and Raymond, 2016; Wik et al., 2016), our measurements might ~~be~~ provide a lower limit of overall pond-CH_4 emissions.

We estimate a CH_4-C flux of $13.38\ ^{15.92}_{10.55}$ mg m^{-2} d^{-1} ($Median\ ^{75\%Percentile}_{25\%Percentile}$) from the merged polygonal pond and $12.96\ ^{15.11}_{10.34}$ – $19.18\ ^{24.47}_{14.26}$ mg m^{-2} d^{-1} from the shores of this pond. This is higher than the fluxes measured by Jammet et al. (2017) from a sub-arctic lake (~~see also Table~~ Tab. 1). The authors report a mean annual CH_4-C flux of 13.42 ± 1.64 mg m^{-2} d^{-1} and a mean ice-free season CH_4-C flux of 7.58 ± 0.69 mg m^{-2} d^{-1}. A study focusing on 32 non-Yedoma thermokarst lakes in Alaska found CH_4-C emissions similar to our results (16.80 ± 8.61 mg m^{-2} d^{-1}, Sepulveda-Jauregui et al. (2015)). Also, a synthesis of 149 thermokarst water bodies north of ∼ 50° reports CH_4-C emissions in the same order of magnitude (27.57 ± 14.77 mg m^{-2} d^{-1}, Wik et al. (2016)). However, there is also a recent study reporting considerably lower CH_4-C emissions of 2.95 ± 0.75 mg m^{-2} d^{-1} in Northern Sweden (Sieczko et al., 2020) and, in contrast, a study finding CH_4-C emissions of up to 6432 mg m^{-2} d^{-1} in North-East Canada (Bouchard et al., 2015). The wide range of ~~waterbody~~ water-body methane emissions cautions us to be careful when generalizing our results even for Samoylov Island, especially since the emissions within the pond are already heterogeneous. Instead, after finding a hotspot in CH_4 emission at the pond shore, we would like to highlight the need for ~~more measurements~~ spatially representative observation and mapping of CH_4 fluxes to understand the variability of pond-CH_4 emissions better.

4.3 Upscaling the CO_2 flux

We upscale the CO_2 emissions for the ~~island~~ river terrace of Samoylov, the area where we have access to the high-resolution ~~land cover~~ land-cover classification. We find that ~~the inclusion of~~ not accounting for pond-CO_2 emission ~~would considerably (11%) decrease the estimate of the~~ leads to an overestimating the polygonal tundra landscape's sink function by 11%. A similar approach by ~~Abnizova et al. (2012)~~ Abnizova et al. (2012) found a potential increase of 35 - 62 % in the estimate of CO_2 emission from the Lena River Delta when including small ponds and lakes into the ~~aquatic~~ landscape CO_2 emission. If we follow the upscaling approach by ~~Abnizova et al. (2012)~~ Abnizova et al. (2012) and consider overgrown water as part of the ponds, we even find a CO_2 emission reduction of 19%. ~~Also, Kuhn et al. (2018) found waterbodies~~ Kuhn et al. (2018) also found water bodies in arctic regions to be an important source of carbon, which could outbalance the tundra's sink function in a future climate. In summary, our results demonstrate that ~~aquatic~~ open-water CO_2 emissions can substantially influence the carbon balance of the polygonal tundra during the growing season. ~~We~~ When looking at the night-time emissions, we find that per gram CO_2-C 0.06 g CH_4-C are emitted from ponds and only 0.02 g CH_4-C from the semi-terrestrial tundra. This finding underlines again, that especially when considering thermokarst ponds, CH_4 emissions are of high interest. Even though mean CH_4 emissions from the semi-terrestrial tundra and open water are of similar magnitude, we expect that the impact of ponds on the carbon balance would be even bigger when accounting for CH_4 due to the locally high emissions~~, and because from the pond more CH_4 gets emitted per mole of~~.

Our results indicate that future studies aiming to capture a representative landscape flux should pay extra attention to the water bodies in their footprint. The CO_2 ~~compared~~ flux from ponds has the opposite sign to the tundra. Consequently, ponds should cover about as much area in the footprint as they do in the landscape. In this way, the chances of capturing CH_4 hotspots are also higher, which can then be investigated more closely.

5 Conclusions

We find that ~~waterbodies~~ thermokarst ponds are a carbon source~~while the~~. At the same time, the surrounding tundra is a carbon sink during the period July – September in agreement with prior studies (Abnizova et al., 2012; Jammet et al., 2017), even if we observe much lower ~~aquatic~~ open-water CO_2 fluxes compared to previous work at the same study site (Abnizova et al., 2012). Using ~~a novel~~ our approach to disentangle the EC fluxes from different land cover classes, we ~~estimate that during our~~ gauge that during the measurement period, not accounting for ponds leads to overestimating the landscape CO_2 sink ~~is reduced~~ by 11%~~when including ponds rather than only considering semi-terrestrial vegetated tundra~~. We expect lakes to have a similar effect on the budget, though a smaller one, since lakes (a) ~~tend to emit less greenhouse gases than ponds (Holgerson and Raymond, 2016; Wik et al., 2016) and (b)~~ cover a similar area as ponds in our study site (Abnizova et al., 2012; Muster et al., 2012) (b) are weaker emitters of greenhouse gases than ponds (Holgerson and Raymond, 2016; Wik et al., 2016) .

In contrast to the spatially more homogeneous CO_2 emissions, small-scale heterogeneity in CH_4 emissions ~~make~~ makes it difficult to find drivers of CH_4 emissions. We cannot pinpoint the drivers behind the high emissions ~~along~~ at parts of the coastline, ~~which might be~~ potentially caused by seep ebullition. Thus, we cannot estimate the impact of this heterogeneity on the landscape scale and, therefore, refrain from upscaling CH_4 emissions. Additionally, the open-water fluxes presented in this paper originate from a single merged polygonal pond since the other ponds surrounding the EC tower are too small to extract their fluxes with the footprint method applied here. So, we do not account for spatial variability of CH_4 emissions between ponds, which can be substantial (Rehder et al., 2021; Wik et al., 2016). However, we note that open-water fluxes were of a similar magnitude as the tundra fluxes. Consequently, the main impact of ponds on the landscape CH_4 budget might be through plant-mediated transport and local ebullition.

While being ill-suited for ~~very small~~ smaller ponds, we want to underline that the EC method is appropriate for observing greenhouse-gas fluxes from ponds with an area as small as $0.024\ \mathrm{km}^2$. The EC method has a higher temporal resolution than the TBL method~~and~~ . It does not disturb the exchange processes like the chamber-flux method, ~~which eliminates~~ eliminating the wind at the water surface. Especially when combining the EC footprint with a land cover classification, we can distinguish the contribution of different land cover classes ~~can be distinguished well , and~~ well and study the fluxes from ponds~~can be studied~~.

We conclude that ponds contribute significantly to the landscape carbon budget. Changes in the Arctic hydrology and the concomitant changes in the ~~waterbody~~ water-body distribution may impact the overall carbon budget of the Arctic and flip a landscape from being an overall carbon sink to becoming an overall carbon source.

Code and data availability. The data has been published at Pangaea (doi will be added as soon as it becomes available). Code can be requested from the authors.

Appendix A: Additional ~~Figures~~figures

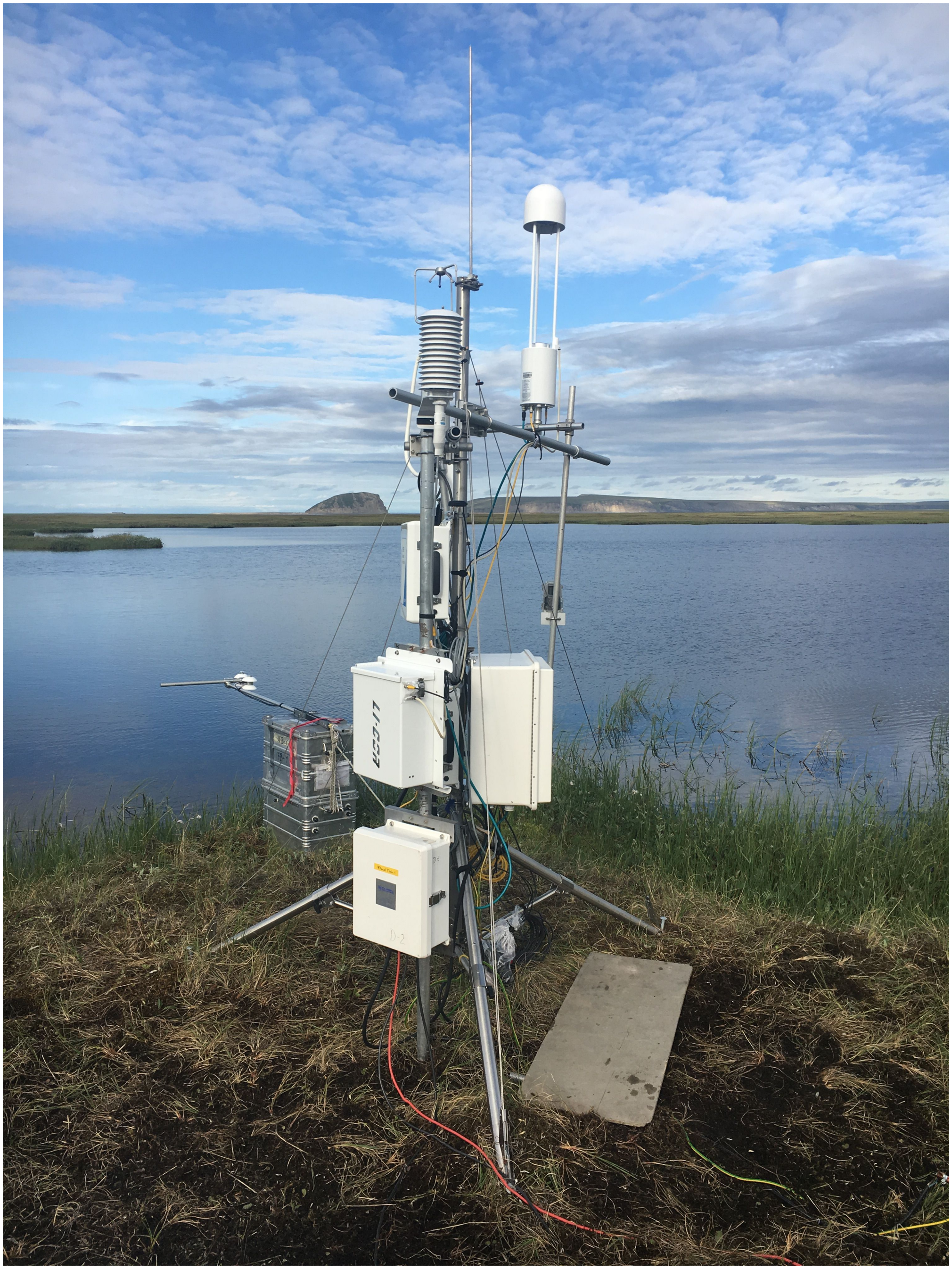

Figure A1. ~~Time line~~ Picture of ~~meteorological conditions during~~ the ~~observation period~~ eddy covariance tower with ~~air temperature~~ the merged polygonal pond in ~~2 meters height (a), wind speed in 3 meters height (b) and photosynthetically active radiation (PAR) (c). Mean values and standard deviation of observations during~~ the ~~past 16 years are plotted as black lines and gray areas~~background. Picture taken on 11 July 2019 by Zoé Rehder.

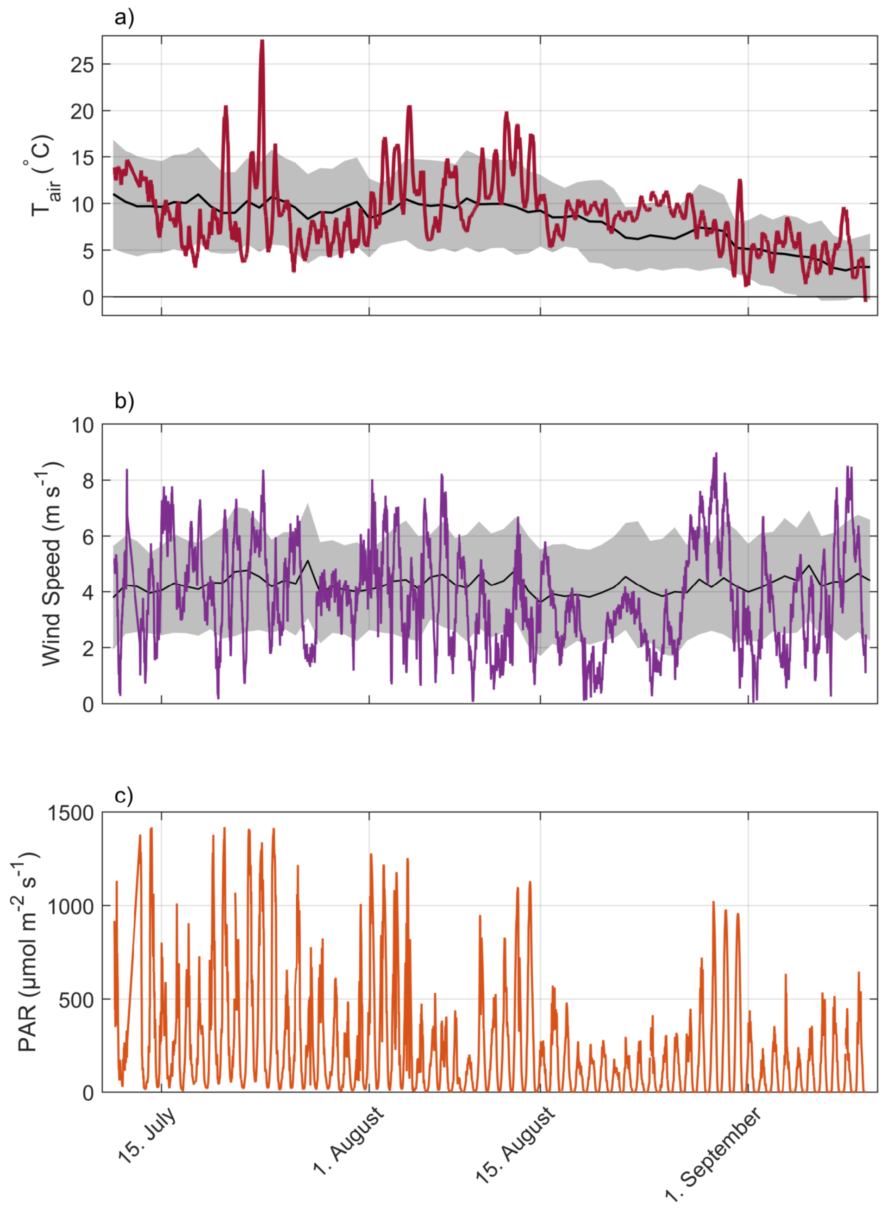

Figure A2. Timeline of observed meteorological conditions during the observation period with air temperature in 2 meters height (a), wind speed in 3 meters height (b) and photosynthetically active radiation (PAR) (c). Mean values and standard deviation of observations during the past 16 years are plotted as black lines and gray areas.

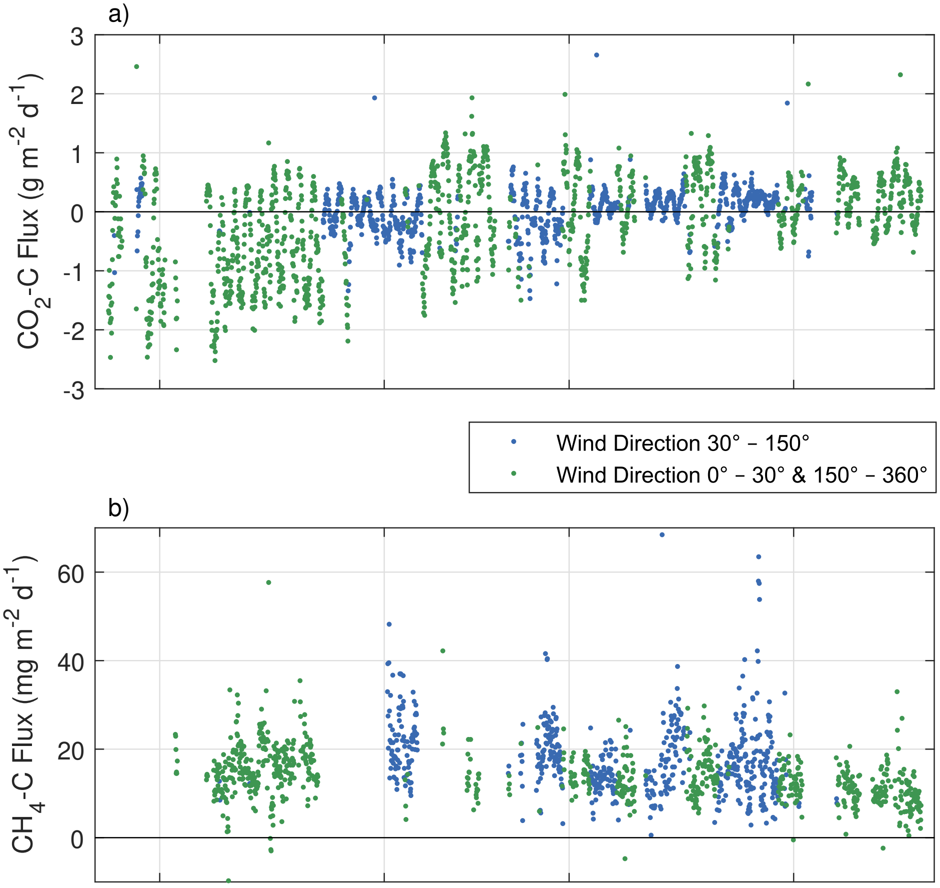

Figure A3. Time series of 30-minute observed CO_2-C flux intervals (a) and CH_4-C flux with a quality flag of 0 or 1. The blue color represents fluxes originating from the wind direction of the lake (30° – 150° wind direction, mostly mixed signals from semi-terrestrial tundra and the lake surface) and the green color represents fluxes originating from all other wind directions.

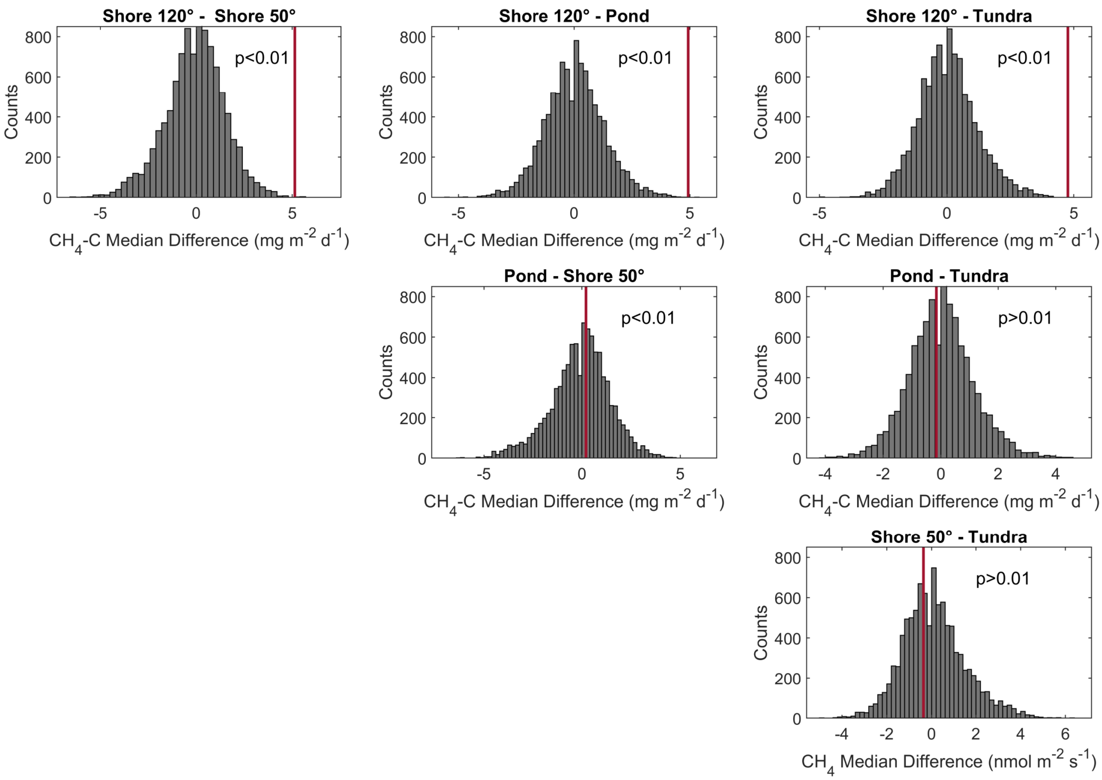

Figure A4. Histogram of permutation tests between the medians of CH_4 emissions from different wind direction classes in figure 6~~, b)~~. All medians from flux observations during moderate wind speed conditions. The observed differences in medians between the different wind direction classes are shown in red vertical bars in each plot.

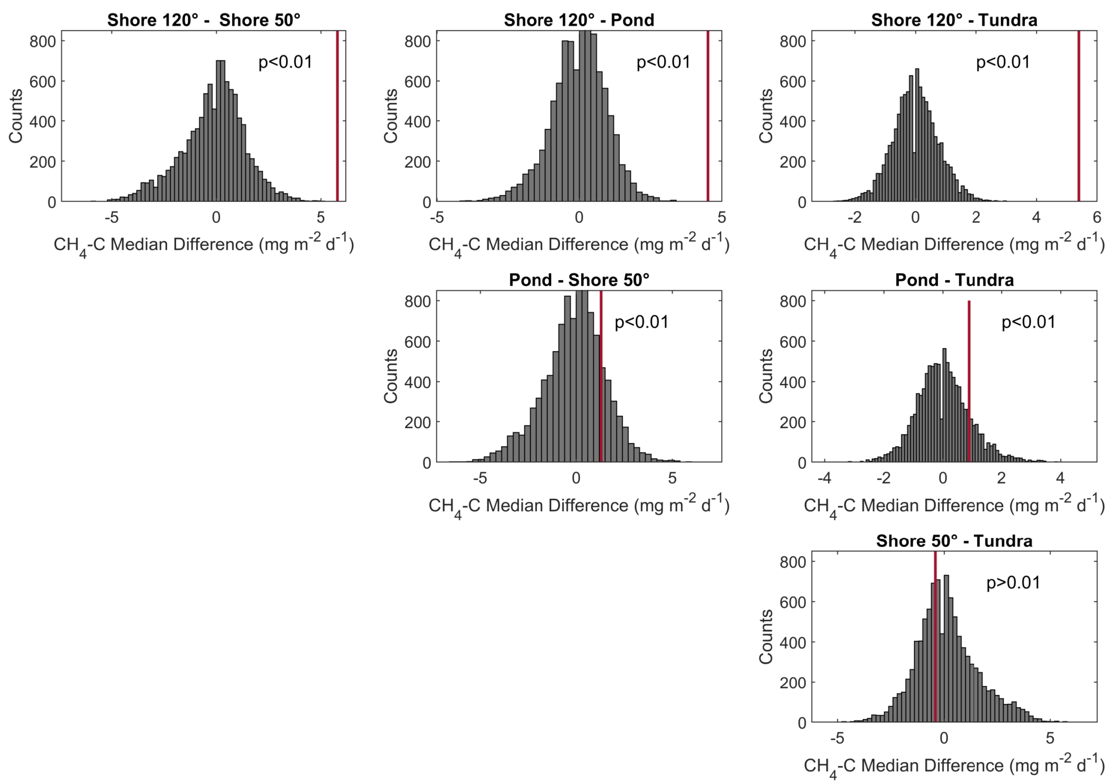

Figure A5. Histogram of permutation tests between the medians of CH_4 emissions from different wind direction classes in figure 6~~, c)~~. All medians from flux observations during moderate air temperature conditions. The observed differences in medians between the different wind direction classes are shown in red vertical bars in each plot.

Author contributions. Zoé Rehder and Lars Kutzbach designed the experiments, Zoé Rehder and Lutz Beckebanze carried out the fieldwork. Zoé Rehder, Lutz Beckebanze, and Lars Kutzbach developed the idea for the analysis, and Christian Wille and Lutz Beckebanze prepared the data. The formal analysis and data visualization were performed by Lutz Beckebanze and Zoé Rehder with supervision by David Holl and Lars Kutzbach. Resources (land cover classification) have been provided by Charlotta Mirbach. Lutz Beckebanze and Zoé Rehder prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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