

# Temporal dynamics and environmental controls of carbon dioxide and methane fluxes measured by the eddy covariance method over a boreal river

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**Abstract.** Boreal rivers and streams are significant sources of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) to the atmosphere. Yet the controls and the magnitude of these emissions remain highly uncertain, as current estimates are mostly based on indirect and discrete flux measurements. In this study, we present and analyse the longest CO<sub>2</sub> and the first ever CH<sub>4</sub> flux dataset measured by the eddy covariance (EC) technique over a river. The field campaign (KITEX) was carried out during June–October 2018 over the River Kitinen, a large regulated river with a mean annual discharge of 103 m<sup>3</sup> s<sup>-1</sup> located in northern Finland. The EC system was installed on a floating platform, where the river was 180 m wide and with a maximum depth of 7 m. The river was on average a source of CO<sub>2</sub> and CH<sub>4</sub> to the atmosphere. The mean CO<sub>2</sub> flux was  $0.36 \pm 0.31$  μmol m<sup>-2</sup> s<sup>-1</sup> and the highest monthly flux occurred in July. The mean CH<sub>4</sub> flux was  $3.8 \pm 4.1$  nmol m<sup>-2</sup> s<sup>-1</sup> and it was also highest in July. During midday hours in June, the river acted occasionally as a net CO<sub>2</sub> sink. In June–August, the nocturnal CO<sub>2</sub> flux was higher than the daytime flux. The CH<sub>4</sub> flux did not show any statistically significant diurnal variation. Results from a multiple regression analysis show that pattern of daily and weekly mean fluxes of CO<sub>2</sub> are largely explained by partial pressure of CO<sub>2</sub> in water (*p*CO<sub>2w</sub>), photosynthetically active radiation (PAR), water flow velocity and wind speed. Water surface temperature and wind speed were found to be the main drivers of CH<sub>4</sub> fluxes.

## 1 Introduction

The global river network covers an area of about 624 000 km<sup>2</sup>, which is approximately 15 % of the global inland water area (Raymond et al., 2013; Verpoorter et al., 2014). Despite their relatively small area, rivers and streams are significant sources of carbon (C) into the atmosphere in the form of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) (Raymond et al., 2013). Prior studies have estimated that 0.23 – 1.8 Pg C yr<sup>-1</sup> is released to the atmosphere from streams and rivers, mainly in the form of CO<sub>2</sub> (Cole et al., 2007; Aufdenkampe et al., 2011; Raymond et al., 2013; Regnier et al., 2013; Lauerwald et al., 2015; Drake et al.,

20 2018). As methane is a more potent greenhouse gas than carbon dioxide, its emission from rivers is of importance although the  $\text{CH}_4\text{-C}$  only accounts for a few percent of the total carbon flux (Cole et al., 2007). The most recent estimate of the outgassing magnitude for  $\text{CO}_2$  was published by Li et al. (2021), who combined studies from 595 streams and rivers. Their global estimate for  $\text{CO}_2$  annual emission is 1.8Pg C of which 72.3 % takes place in streams (Strahler orders 1–3) (Li et al., 2021). For  $\text{CH}_4$ , the most recent outgassing estimate is 27.9 Tg  $\text{CH}_4$  per year (Rocher-Ros et al., 2023).

25 By far most of the river gas flux studies so far have been conducted using floating chambers that are point measurements in time and space (Bastviken et al., 2015; Lorke et al., 2015). In addition, the flux measurements and gas sampling tend to concentrate on daytime hours (Gómez-Gener et al., 2021) and mostly during calm and moderate wind speed with good weather conditions. Due to the magnitude of surface-layer turbulence and the processes producing or consuming  $\text{CO}_2$  or  $\text{CH}_4$  being dependent on location and time (Rocher-Ros et al., 2019; Gómez-Gener et al., 2021; Attermeyer et al., 2021), there  
30 is inherently large spatial and temporal variability in the flux magnitude, which may not be captured with floating chambers (Hall and Ulseth, 2019). The eddy covariance (EC) method, which provides flux estimates for a certain averaging period and represents a much larger spatial domain than chambers, has been utilised over a river so far only once for  $\text{CO}_2$  flux (Huotari et al., 2013), and never for  $\text{CH}_4$ . Therefore, due to the lack of continuous and long term flux timeseries, knowledge gaps exist in resolving the diurnal, seasonal and interannual variability of the air–water gas exchange and in the significance of different  
35 physical and biogeochemical processes in rivers and streams of different sizes.

To address this gap, we conducted an experiment on the subarctic River Kitinen in northern Finland during June–October 2018 in the Kitinen Experiment (KITEX) campaign. The goal of the campaign was to measure and quantify the  $\text{CO}_2$  and  $\text{CH}_4$  fluxes ( $F_{\text{CO}_2}$  and  $F_{\text{CH}_4}$ , respectively) with an EC system on a floating platform as well as the physical forcings driving the fluxes. The aims of this study are to provide four-month time series of both  $\text{CO}_2$  and  $\text{CH}_4$  fluxes and to quantify the response  
40 of the fluxes to different environmental drivers. In addition, we present the diurnal patterns of the gas fluxes, analyse their possible causes, and discuss to what extent the under-representation of flux temporal dynamics in existing database, largely based on discrete sampling, may bias estimates of  $\text{CO}_2$  and  $\text{CH}_4$  emissions from river systems. Finally, we propose a new approach to attempt to minimize the effect of a limited fetch on the measured fluxes, providing more information of the use of EC technique in relatively small inland water bodies.

## 45 2 Material and methods

### 2.1 Site description

The River Kitinen in northern Finland is 235 km long and has a catchment area of 7672 km<sup>2</sup> (Fig. 1a). The catchment area consists mostly of managed boreal forest with Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) as the main tree species, wetlands of which a large portion is drained, small streams and rivers, some low mountains and a few small settlements.  
50 Forests cover approximately 67 % and wetlands 25 % of the catchment. The soil in the catchment area consists mainly of sandy moraine and peat. The catchment area is relatively flat, the height above sea level being 100–200 m in the south and 200–300 m in the north and exceeding 400 m only in a few places. Consequently, the mean slope of the river is just 0.5 m km<sup>-1</sup>. The

River Kitinen is heavily regulated with altogether seven hydropower plants and corresponding reservoirs along its length. The river is a tributary of the larger River Kemijoki.

55 Kitinen's catchment area belongs to the subarctic climate zone (Köppen classification Dfc). The annual mean temperature (related to the Finnish Meteorological institute's reference period 1991–2020) is 0.3°C and the annual mean precipitation is 543 mm. Permafrost does not exist in the region. The vegetation growing period in the area normally lasts from mid-May until late September. The river freezes every winter, usually in October–November and the ice breakup normally takes place in May. In 2018, the breakup occurred in mid-May.

60 The experiment site (67.37° N, 26.62° E, 173 m above sea level) was located next to the Finnish Meteorological Institute's research and weather station in Tähtelä (Figs. 1b–c), 5 km south of the town of Sodankylä. At the experiment location the river is 180 m wide and forms a straight section extending approximately 600 m upstream and 1000 m downstream from the site. The direction of the river at the site is roughly north-northwest–south-southeast and it flows towards the south. The mean annual discharge, measured at the closest power plant downstream, is 103 m<sup>3</sup> s<sup>-1</sup>. The maximum depth at the site is 7 m. The  
65 river bed consists mainly of sand with some overlaying biological deposits. The River Kitinen's Strahler stream order at the site is 5, based on hydrographical data that include headwater streams with a catchment area larger than 10 km<sup>2</sup>.

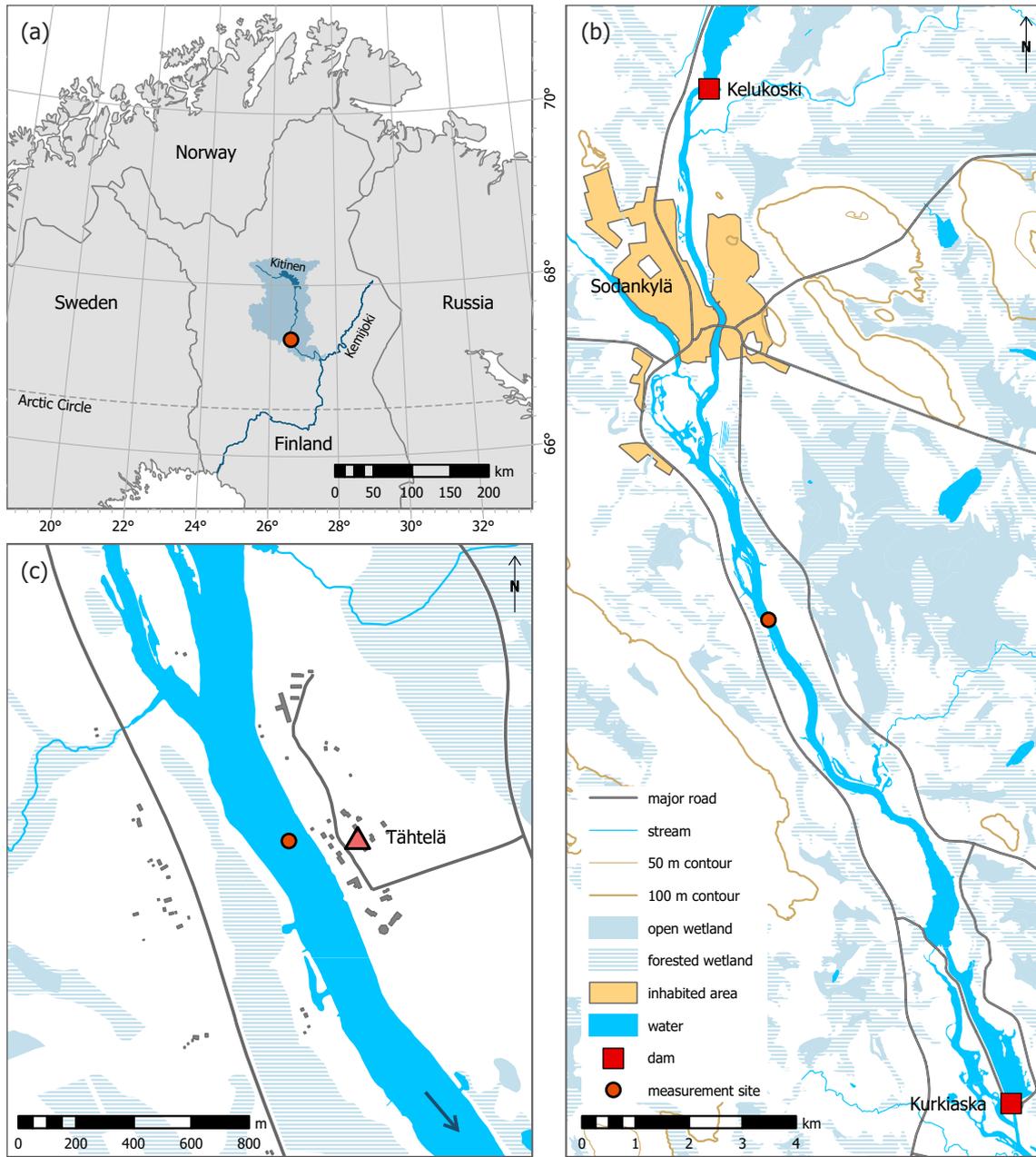
The closest hydropower plants to the site are located 11 km upstream and 11 km downstream. The water flow velocity at the experiment site was almost completely controlled by the hydropower dam regulation downstream. Flow regulation in the river followed a certain pattern where the flow would be small or completely halted during most nights (Guseva et al., 2021).

70 The eddy covariance, meteorological and water flow measurements were conducted on a floating platform, located about 70 m from the eastern river bank, where the water depth was 4.5 m. The platform was 6 m × 3 m and was constructed of a marine plywood deck on top of plastic pontoons. The deck was 0.5 m above the water surface. The platform was anchored with four concrete blocks and held in its position with four anchor lines that each also had a large buoy attached, keeping the line tight. The anchoring blocks had a mass of 200 kg and were placed 20–30 m away from the platform's corners. The anchoring made  
75 the platform very stable and the motion of the platform was minimal. Electricity was provided to the platform by a power cable.

The campaign lasted from 1 June until 17 October 2018. Eddy covariance measurements took place from 1 June to 2 October.

## 2.2 Eddy covariance measurements

The EC system measuring water–atmosphere turbulent fluxes was mounted on a mast on the southern side of the platform. This installation consisted of an ultrasonic anemometer (uSonic-3 Scientific, METEK Meteorologische Messtechnik GmbH,  
80 Elmshorn, Germany) for measuring the wind speed in three Cartesian coordinates  $u$ ,  $v$  and  $w$  and the sonic temperature  $T_s$ , an enclosed-path gas analyser (LI-7200RS, LI-COR Biosciences, Inc., Lincoln, Nebraska, USA) for measuring carbon dioxide and water vapour mole fractions  $\chi_{\text{CO}_2}$  and  $\chi_{\text{H}_2\text{O}}$ , and a closed-path gas analyser (G1301-f, Picarro, Inc., Santa Clara, California, USA) for measuring methane and water vapour mole fractions  $\chi_{\text{CH}_4}$  and  $\chi_{\text{H}_2\text{O}}$ . The centre of the sonic anemometer was 1.82 m above the water surface. The gas analyser sampling line inlets were placed 2 cm below the sonic anemometer and their  
85 horizontal separation from the centre of the sonic anemometer was 3 cm. The inlets were equipped with rain guards and fine mesh filters. The LI-7200RS's sampling line was made of AISI 316 stainless steel. Its length was 1.0 m, it was 6.4 mm in outer



**Figure 1.** (a) Location of the River Kitinen (blue line) and its catchment area (light blue area) in northern Finland. The site of the experiment is marked with a red dot. The larger River Kemijoki is drawn with a dark blue line. (b) General area of the measurement site. Hydropower plants closest to the site are indicated with red squares. (c) Immediate surroundings of the experiment site. The arrow indicates the flow direction. The red triangle shows the location of the Tähtelä weather station. Buildings are marked with grey polygons. Map data sources: (a) naturalearthdata.com (base map); Finnish Environment Institute, 12/2020 (hydrographical data). (b–c) National Land Survey of Finland Topographic Database, 12/2020.

and 4.4 mm in inner diameter, and it was heated at a constant rate of  $6 \text{ W m}^{-1}$ . The flow rate was  $12 \text{ l min}^{-1}$ . The G1301-f sampling line was made of PTFE (teflon), it was 10 m in length, 6.4 mm in outer diameter, 4.4 mm in inner diameter and was heated at a constant rate of  $9.5 \text{ W m}^{-1}$ . The flow rate was  $16 \text{ l min}^{-1}$ . An inclinometer (DOG2 micro-electro-mechanical system, Measurement Specialties, Inc., Hampton, Virginia, USA) was used for measuring the pitch and roll of the platform.

The sampling rate of ultrasonic anemometer, gas analysers and the inclinometer was 10 Hz and were recorded on mini-computer by using an in-house data logging software.

A calibration system for LI-7200RS began operating on 29 August until the end of the campaign. The calibration consisted of driving 5 min of synthetic air with 0 ppm of  $\text{CO}_2$  and 5 min of synthetic air with 450 ppm of  $\text{CO}_2$  through the gas analyser once a day. Calibration was solved for both the offset and the span in the  $\text{CO}_2$  mixing ratio. The offset was negligible. In contrast, there was 1.3 % span correction applied to the measured  $\text{CO}_2$  mole fraction data. The G1301-f was not calibrated on field but instead the factory calibration was used.

### 2.3 Eddy covariance data processing

EC fluxes were calculated using the EddyUH software (Mammarella et al., 2016), following the state of art methodologies (Sabbatini et al., 2018; Nemitz et al., 2018). Rawdata were despiked based on the maximum difference allowed between two subsequent data points, according to the threshold values listed in Table 1. The dilution and spectroscopic correction (Chen et al., 2010) were applied point-by-point to the measured  $\text{CH}_4$  mole fraction using the simultaneous  $\text{H}_2\text{O}$  mole fraction measured in the sampling cell of the Picarro analyser. The LI-7200RS internally corrects the water-induced density effect and gives as an output the dry mole fraction of  $\text{CO}_2$ . No density corrections were therefore needed for  $\text{CO}_2$  (Burba et al., 2012). Although operated, the inclinometer data were not used for correcting the wind velocity components. It was checked from cospectra of  $\overline{u'w'}$  and  $\overline{v'w'}$  that the differences between the inclinometer-corrected and uncorrected velocities were only random. Instead, the inclinometer data was used in screening out the occasions when the movement of the platform was too big, i.e. when there were persons on the platform. A crosswind correction of sonic temperature was applied according to Liu et al. (2001). Additionally, a double coordinate rotation was applied to the sonic anemometer data by forcing the mean values of lateral ( $v$ ) and vertical ( $w$ ) velocity components of wind to zero.

Gas fluxes were calculated from the covariance between the vertical wind speed  $w$  and the gas dry mole fraction  $\chi$ , multiplied by the molar density of air  $\rho_a$ , as

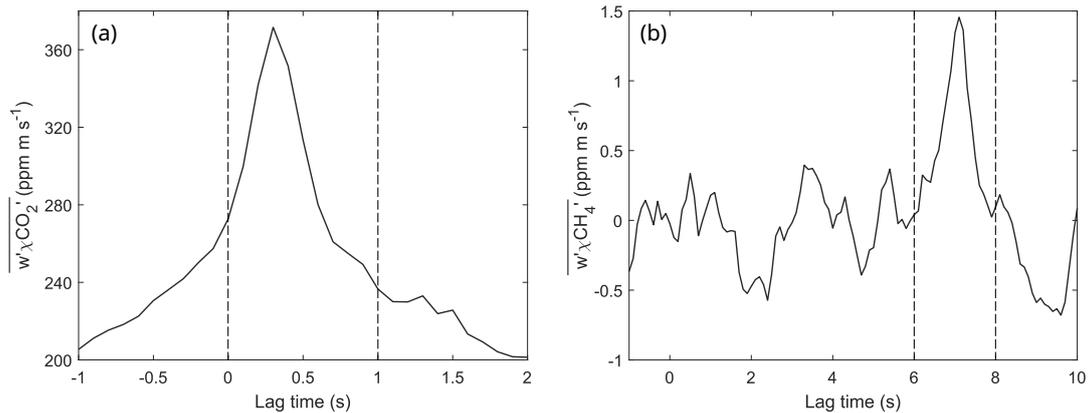
$$F_\chi = \rho_a \overline{w'\chi'}, \quad (1)$$

where the overbar denotes the time average and the prime the deviation from the mean. An averaging time of 30 minutes was used. The time series were linearly detrended so that the turbulent fluctuation in equation (1) was defined as the deviation from the linear trend. Per definition, a positive flux indicates an upward flux (from the surface to the atmosphere).

Before calculating the covariance, the time lag between  $w$  and  $\chi$  was removed. The time lag was determined by finding the maximum of the cross-covariance of  $w$  and  $\chi$  within a given lag window (Aubinet et al., 2000). Examples of cross-covariance functions are shown in Fig. 2. Due to the low signal-to-noise ratio and in order to reduce the possible mirror effect of the fluxes

**Table 1.** Threshold values for detecting spikes in different variables.

Variable	Threshold
$u, v$	$10 \text{ m s}^{-1}$
$w$	$7 \text{ m s}^{-1}$
$T_s$	$10^\circ\text{C}$
$\chi_{\text{CO}_2}$	100 ppm
$\chi_{\text{H}_2\text{O}}$ (Li-7200RS)	$50 \text{ mmol mol}^{-1}$
$\chi_{\text{CH}_4}$	100 ppb
$\chi_{\text{H}_2\text{O}}$ (G1301-f)	$50 \text{ mmol mol}^{-1}$



**Figure 2.** Example cases of maximising the cross-covariance between (a)  $\text{CO}_2$  and  $w$  and (b)  $\text{CH}_4$  and  $w$ . The dashed lines mark the boundaries between which the maximum was searched. In these cases, the location of the cross-covariance peak, i.e. the lag time for these averaging periods, was  $t_{\text{lag}} = 0.3 \text{ s}$  for  $\text{CO}_2$  and  $t_{\text{lag}} = 7.1 \text{ s}$  for  $\text{CH}_4$ .

120 around zero (Kohonen et al., 2020), a constant lag of 0.34 s was used for  $\text{CO}_2$  and 7.0 s for  $\text{CH}_4$ . These values were calculated as the mean values of estimated time lag distribution. For  $\text{H}_2\text{O}$ , a relative humidity (RH) dependent time lag, varying from 0.30 s to 1.8 s, was used in order to account for the  $\text{H}_2\text{O}$  sorption in the sample line.

Fluxes were corrected for both low and high frequency attenuation. The actual unattenuated flux  $F$  is calculated from the measured flux  $F_\chi$  as

$$125 \quad F = \frac{F_\chi}{F_a}, \quad (2)$$

where  $F_a$  is the flux attenuation. It is defined as the integral of a model cospectrum  $C_{\text{model}}(f)$  and the total transfer function TF, normalised by the model cospectrum:

$$F_a = \int_0^\infty C_{\text{model}}(f) \text{TF}(f) df \Big/ \int_0^\infty C_{\text{model}}(f) df. \quad (3)$$

TF is a product of the high- and low-frequency transfer functions that describe the attenuation at different frequencies ( $f$ ).

- 130 The low-frequency flux attenuation stems from the linear detrending of the original timeseries (Rannik and Vesala, 1999). The theoretical transfer function in this case is

$$\text{TF}_{\text{LF}} = 1 - \frac{\sin^2(\pi f T_{\text{av}})}{(\pi f T_{\text{av}})^2} - 3 \frac{[\sin(\pi f T_{\text{av}}) - \pi f T_{\text{av}} \cos(\pi f T_{\text{av}})]^2}{(\pi f T_{\text{av}})^4}, \quad (4)$$

where  $T_{\text{av}}$  is the averaging time. The high-frequency correction of fluxes was solved using an experimental transfer function (Aubinet et al., 2000). It is assumed that the temperature cospectrum  $C_{w\theta}$  is unattenuated and therefore used as reference

- 135 cospectrum. The measured transfer function is then

$$\text{TF}_{\text{meas}} = \frac{N_{\chi} C_{w\chi, \text{meas}}}{N_{\theta} C_{w\theta}}, \quad (5)$$

where  $N_{\chi}$  and  $N_{\theta}$  are normalisation factors equal to the covariances  $\overline{w'\chi'}$  and  $\overline{w'\theta'}$ , respectively. The following functional form was then fitted to the measured values of Eq. (5)

$$\text{TF}_{\text{HF}} = \frac{1}{(1 + 2\pi f \tau)^2}, \quad (6)$$

- 140 where  $\tau$  is the response time. Similarly as with the lag time determination, the response time was not affected by sorption effect in the case of  $\text{CO}_2$  and  $\text{CH}_4$  fluxes and a constant response time  $\tau = 0.185$  s for  $\text{CO}_2$  and  $\tau = 0.2$  s for  $\text{CH}_4$  could be used. In contrast,  $\tau$  for  $\text{H}_2\text{O}$  is relative humidity-dependent (Mammarella et al., 2009). In this case,  $\tau$  was determined by dividing the measured cospectra into six  $RH$  classes and calculating the bin mean. Then, a curve of the form

$$\tau_{\text{H}_2\text{O}} = b_1 + b_2(RH/100)^{b_3} \quad (7)$$

- 145 with  $b_1 = -0.057$ ,  $b_2 = 0.79$ ,  $b_3 = 1.6$  was fitted to the averaged data.

The model cospectrum in equation (3) was determined by fitting the function proposed by Kristensen et al. (1997) to the measured normalised temperature cospectrum  $C_{w\theta}$

$$C_{\text{model}}(n) = \frac{a \cdot \frac{2\pi}{z} n}{[1 + (2\pi n L)^{2\mu}]^{7/(6\mu)}}, \quad (8)$$

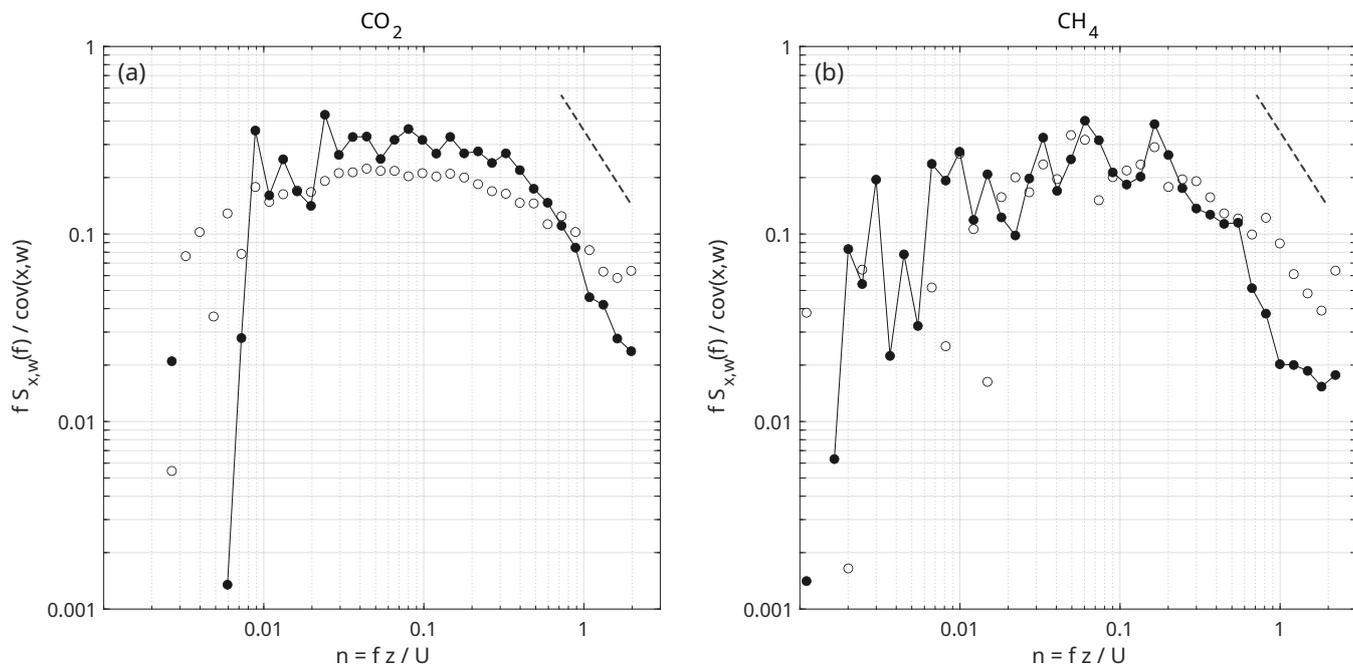
where  $n = zf/U$  is the normalised frequency,  $z$  is the measurement height and  $U$  is the mean wind speed. The fit parameters

- 150 were  $a = 6.78$  m,  $L = 1.35$  and  $\mu = 0.32$  for unstable cases and  $a = 57.00$  m,  $L = 1.84$  and  $\mu = 0.17$  for stable cases.

Mean cospectra of  $\text{CO}_2$  and  $\text{CH}_4$  follow the theoretical shape and exhibit a well-defined inertial subrange (Fig. 3).

The following criteria were used in the post-processing quality control of the fluxes: skewness  $SK$  and kurtosis  $KU$  of both  $w$  and the dry mole fraction  $\chi$  of the gas in question ( $-2 < SK < 2$ ,  $1 < KU < 8$ ) (Vickers and Mahrt, 1997), flux stationarity ( $FST \leq 1$ ) (Foken and Wichura, 1996), the number of spikes ( $\leq 1800$  in a 30-minute averaging period), the wind direction,

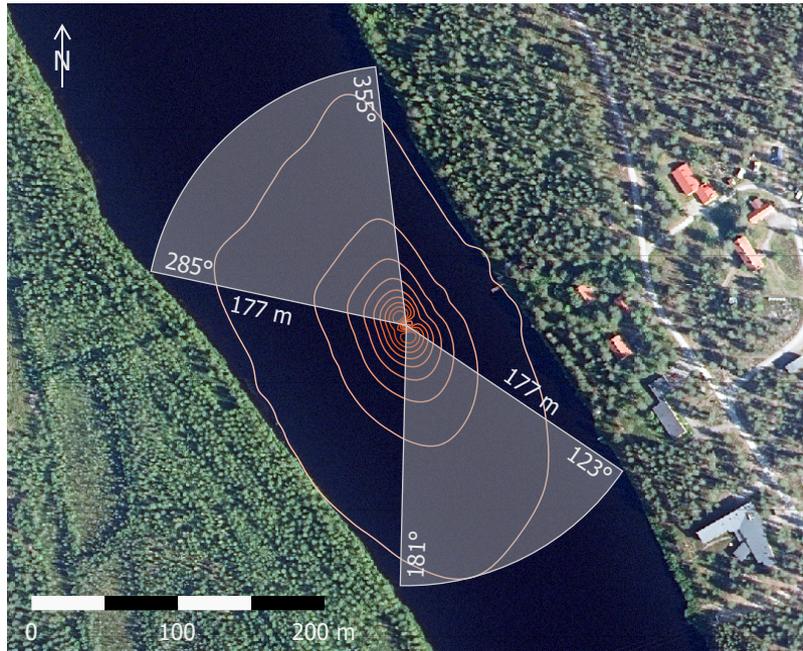
- 155 and occasions when the platform swayed too much, most often due to persons on the platform. As suggested by Erkkilä et al. (2018), additional filtering was done based on threshold values of standard deviation of carbon dioxide ( $\sigma_{\chi\text{CO}_2}$ ) and methane  $\sigma_{\chi\text{CH}_4}$  mixing ratios. The criteria retained 30 min flux values when  $\sigma_{\chi\text{CO}_2} < 1$  ppm and  $\sigma_{\chi\text{CH}_4} < 0.013$  ppm.



**Figure 3.** Mean normalised cospectra of (a)  $\chi\text{CO}_2$  and  $w$  and (b)  $\chi\text{CH}_4$  and  $w$  from 19–22 July when the fluxes were at their highest. The black circles represent the mean cospectra. The white circles are the mean normalised cospectra of the sonic temperature and  $w$ . The dashed lines show the  $-4/3$  slope. The cospectra are presented by the normalised dimensionless frequency  $n = fz/U$ , where  $f$  is the natural frequency,  $z$  is the measurement height and  $U$  is the wind speed.

In order to find acceptable wind sectors, the flux footprint model by Kljun et al. (2015) was used. Parameters for the footprint calculation were the friction velocity  $u_*$ , standard deviation of lateral wind velocity  $\sigma_v$ , wind direction and the calculated  
160 Obukhov length  $L_{MO}$ . We assume a constant boundary layer height  $h_{BL} = 1000$  m and roughness length  $z_0 = 0.01$  m. The full dataset of these variables was used in the footprint analysis. The resulting footprint climatology, depicted in Fig. 4, is roughly oval-shaped with the long axis approximately along the river. Estimates for the footprint are generally not applicable with changing roughness, therefore, the river bank directions are excluded from further flux analysis. The longest distance to the 90 % footprint line at the southern side over the river is 177 m. Sectors where the river bank was further than 177 m from the  
165 platform were accepted. The two sectors are  $123^\circ$ – $181^\circ$  and  $285^\circ$ – $355^\circ$ .

However, there were numerous cases where the average 30-minute wind direction was seemingly from an accepted sector, but the instantaneous wind direction was at least partly from a rejected sector. In some cases, this had a considerable effect on the measured concentration and flux values, as the surrounding land was a source or sink of carbon dioxide, depending on the time of the day, and a source of methane. In addition, the magnitude of these sources or sinks can be larger than in the river. An  
170 example of such a case is shown in Fig. A1 when an air mass from the land caused an abrupt increase in the  $\text{CO}_2$  mixing ratio and decrease in temperature after 23:53 UTC. In this case, the stationarity value of the  $\text{CO}_2$  flux was 0.35, i.e. it passed the criterium  $\text{FST} < 1$ . To mitigate this effect, the following approach was used. Fluxes were calculated for 5-minute subintervals.



**Figure 4.** Flux footprint climatology. The curves show the footprint percentiles at 10 % intervals, starting from the outermost 90 % footprint. The grey sectors are the accepted wind directions. Image contains data from the National Land Survey of Finland Topographic Database, 12/2020.

If the mean wind direction fell within the accepted sectors in all of the six subintervals, the corresponding 30-minute flux value was retained. If more than one but less than six subintervals fell within the accepted sectors, their average was used as the value for the flux for that 30-minute record. The record with one or none accepted 5-minute subintervals were discarded. This method still potentially leaves intermittent periods of wind from land for less than five minutes in the accepted data, but reduces their amount and their contribution to the final fluxes. Evidently, when the average of the 5-minute fluxes was used, it is a better approximation of the river surface exchange than the corresponding 30-minute flux as the difference between the 30-minute fluxes and the averaged 5-minute fluxes reduces with an increasing number of averaged 5-minute intervals (Fig. A2).

After the flux calculation and the raw data quality control, there were altogether 4534 30-minute flux data records. Table 2 summarises all flux quality control criteria and how much of the original 30-minute data retained after applying the criteria. In total, 43.9 % of the original  $F_{\text{CO}_2}$  records and 38.9 % of the original  $F_{\text{CH}_4}$  records remained after the quality control. Wind direction and standard deviation of gas mixing ratios were the most prominent criteria and removed approximately one fourth and one fifth of all the data, respectively. Most of the applied criteria overlapped with each other.

#### 2.4 Ancillary measurements and data processing

Ambient air temperature ( $T_a$ ) and relative humidity were measured with a Rotronic HC2-S3C03 probe (Rotronic AG, Bassersdorf, Germany), mounted inside a Young model 41003 (R. M. Young Company, Traverse City, Michigan, USA) multi-plate

**Table 2.** The applied post-processing quality criteria and the amount of data they retain. SK: skewness, KU: kurtosis, WD: wind direction, FST: flux stationarity.

Criterion	Data records retained	% of all data
SK( $w$ ) $\in (-2, 2)$	4534	100
KU( $w$ ) $\in (1, 8)$	4468	98.5
WD	3265	72.0
too large movement of platform	4404	97.1
SK( $\chi_{\text{CO}_2}$ ) $\in (-2, 2)$	4230	93.3
KU( $\chi_{\text{CO}_2}$ ) $\in (1, 8)$	4111	90.7
FST( $F_{\text{CO}_2}$ ) $< 1$	3921	86.5
SK( $\chi_{\text{CH}_4}$ ) $\in (-2, 2)$	3892	85.8
KU( $\chi_{\text{CH}_4}$ ) $\in (1, 8)$	3597	79.3
FST( $F_{\text{CH}_4}$ ) $< 1$	3668	80.9
$\sigma\chi_{\text{CO}_2} < 1$ ppm	3559	78.5
$\sigma\chi_{\text{CH}_4} < 0.013$ ppm	3674	81.0
total ( $F_{\text{CO}_2}$ )	1904	41.9
total ( $F_{\text{CH}_4}$ )	1686	37.2

radiation shield on the platform's north-eastern corner.  $T_a$  and RH were available only after 15th of June. Before that, the sonic temperature and humidity calculated from  $\chi_{\text{H}_2\text{O}}$ , measured with the LI-7200RS, were used instead. Atmospheric pressure  $p_{\text{atm}}$  and precipitation were measured at the Tähtelä weather station. Photosynthetically active radiation (PAR) in water was measured with two LI-192 [and one LI-193](#) sensors (LI-COR Biosciences, Inc., Lincoln, Nebraska, USA). The sensors were hanging from wires at 0.3 m and 1.0 m depths ([LI-192](#)) [and at 0.65 m \(LI-193\)](#) on a beam on the southern side of the platform. In the analysis, we used the sensor at 0.3 m.

Measurements of water side  $\text{CO}_2$  partial pressure ( $p\text{CO}_2$ ) were done by using an off-axis integrated cavity output spectrometer (Ultraportable Greenhouse Gas Analyzer – UGGA, Los Gatos Research, Inc., Santa Clara, California, USA) that was connected to the headspace of an equilibrator consisting of a floating Plexiglas chamber ( $130 \times 500 \times 500$  mm) sticking about 50 mm into the water, leaving a headspace volume of about 20 l. The air in the headspace was circulated through the UGGA in a closed loop where the intake tube was fitted with a membrane (Accurel Polypropylene Capillary Membrane, Membrana GmbH, Germany) that prevented water from entering the UGGA. In order to increase the response time of the equilibrium con-

200 centration, a diffuser was placed in the water about 30 mm below the surface just beneath the chamber. The diffuser consisted of a disc covered by a membrane with a large number of small holes. An external pump forced the air from the headspace through the diffuser at a rate of  $2.5 \text{ l min}^{-1}$ . A laboratory test showed that the time response of the system was about 40 minutes for 95 % change in concentration. The UGGA was connected to the equilibrator during 5 minutes every 20 minutes. The first 2 minutes after connection was skipped to allow the gas analyzer to adapt to the new condition (ambient air concentrations at 205 0.40 m and 2.40 m above the water surface were also monitored with the same system) allowing 3 minutes for averaging. The UGGA was calibrated against reference gases (562–1188 ppm  $\text{CO}_2$ ) with a specified accuracy of 2 %.

A water temperature chain was set up 100 m upstream of the platform. It consisted of five temperature loggers of the type RBR Solo (RBR Ltd. Ottawa, Ontario, Canada). The loggers were placed on a taut line mooring at depths of 0.35 m, 1.35 m, 2.35 m, 3.35 m and 4.35 m (6 June to 17 June) and 0.07 m, 1.05 m, 2.05 m, 3.05 m and 4.05 m (17 June onwards). The topmost 210 measurement was used as the surface temperature. The water flow velocity was measured with a acoustic Doppler velocimeter (Nortek Vector, Nortek AS, Rud, Norway) which was installed on a beam on the north-western corner of the platform, facing down (Guseva et al., 2021). The depth of the measurements was 0.4 m below the surface.

Spikes in ancillary data were identified with a MATLAB Hampel filter. The filter uses a moving window and identifies outliers with a standard deviation criterium. The filter parameters were hand-tuned for each variable. Spikes were replaced 215 with linearly interpolated values.

## 2.5 Multiple regression analysis

To study the drivers of the gas exchange, multiple linear regression between the fluxes and their possible drivers were tested. The driving variables were  $T_{\text{surf}}$ , PAR, wind speed ( $U$ ), water flow speed ( $U_w$ ),  $p\text{CO}_{2w}$  and precipitation (prec). All fluxes and environmental variables were distributed normally at a 95 % confidence level, thus making it possible to use regression models. 220 Regressions were calculated on 24-hour and seven-day timescales, chosen to average diel and synoptic variations. Averages were accepted when the data coverage was more than 30 %. Outliers in the averages were removed before calculating the regression models. The model results were ranked by the adjusted coefficient of determination  $R_{\text{adj}}^2$ . The adjusted  $R^2$  was used instead of the ordinary  $R^2$  to account for the artificial inflation of  $R^2$  when more variables are added into a model.

Due to intercorrelation among the driving variables themselves, similar multiple regression calculations were conducted also 225 for  $p\text{CO}_2$  with water temperature, PAR, precipitation, wind speed and water flow speed as the driving variables.

Additionally, the dependence of the diurnal variability of  $p\text{CO}_{2w}$ ,  $F\text{CO}_2$  and  $F\text{CH}_4$  on the drivers was tested similarly as with the 1-day and 7-day means. In calculating the cycles, the mean of each individual day was first subtracted in order to analyse only the daily variability and not the longer-term changes in the baseline of the variables. The same driving variables were used in these calculations except for precipitation for which there were only daily values available. All of the driving 230 variables exhibited diurnal variability.

### 3 Results

#### 3.1 Environmental conditions

The 30-minute average air temperature rose from 10 °C at the beginning of the campaign to 30 °C in early August and then fell slightly below the freezing point towards the end of the campaign (Fig. 5a). The river surface temperature was 10 °C at the start of the campaign, reached its maximum value of 21.9 °C in the beginning of August and then fell close to the freezing point towards the end of the campaign (Fig. 5a), following closely the seasonal variation of air temperature. The water temperature difference between the river surface and the bottom was less than 2.0 °C at any time during the campaign (Fig. 5b). Stratification, defined as when the temperature difference between surface and bottom exceeded 0.05 °C, occurred when the flow was reduced, during 38 % of the campaign (Guseva et al., 2021).

The surface water at the platform was constantly supersaturated with CO<sub>2</sub> with respect to the atmosphere (Fig. 5c). The CO<sub>2</sub> partial pressure in the water  $p_{\text{CO}_2, \text{w}}$  varied between 550 and 1323 ppm, the lowest values occurring in June and the highest in July. The daily variation of  $p_{\text{CO}_2, \text{w}}$  ranged from 5 to 225 ppm.

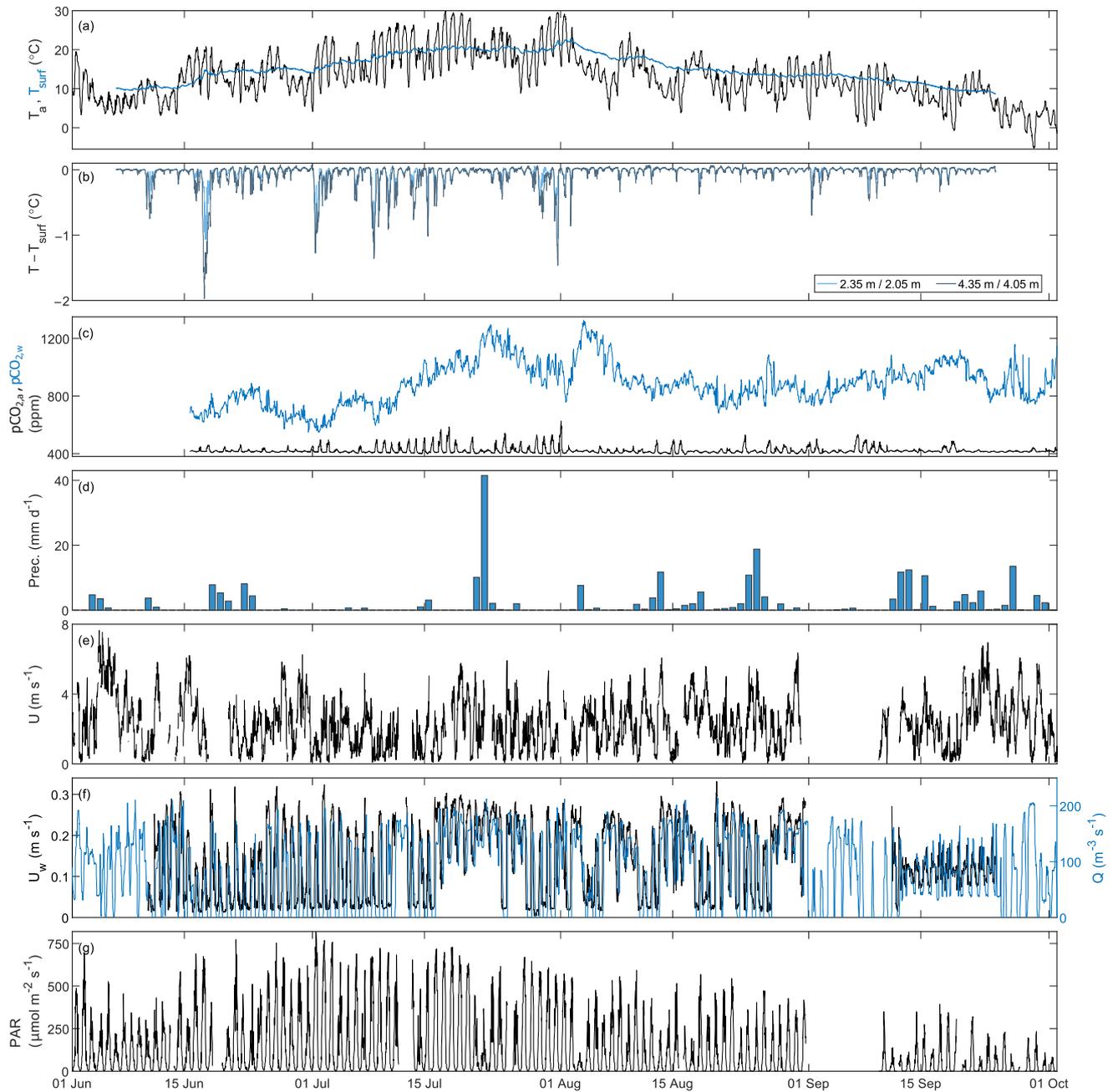
The monthly precipitation was 43.7 mm in June, 61.4 mm in July, 75.9 mm in August and 78.5 mm in September–October (Fig. 5d). These correspond to approximately 25 % less than the average precipitation in June and July and about 40 % and 50 % more than average in August and September, respectively. In July, there was one heavy rain event that brought 41.5 mm of precipitation during one day.

The 30-minute mean wind speed varied between 0 and 8 m s<sup>-1</sup> during the campaign months (Fig. 5e). The wind speed had both diurnal and synoptic variations and was largely channeled along the river (Fig. 6). The water flow speed varied from 0 to 0.33 m s<sup>-1</sup> (Fig. 5f), showing as well a diel pattern due to the downstream dam operation (Guseva et al., 2021). Finally, underwater PAR measurements show expected diurnal and seasonal variations (Fig. 5g), with largest daytime values recorded in July (760 μmol m<sup>-2</sup> s<sup>-1</sup>) and the lowest at the end of the field campaign in September (60 μmol m<sup>-2</sup> s<sup>-1</sup>). [The net radiation \(Fig. S1a\) had also distinct diurnal and seasonal variability, as did PAR at all the measured depths \(Fig. S1b\).](#)

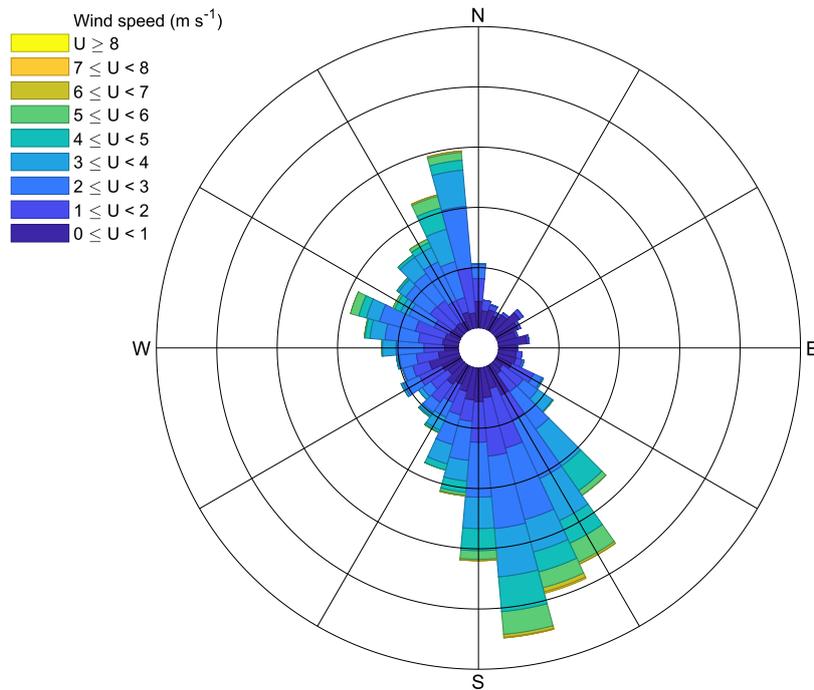
#### 3.2 CO<sub>2</sub> and CH<sub>4</sub> fluxes

The quality-controlled 30-minute fluxes of CO<sub>2</sub> and CH<sub>4</sub> as well as their daily averaged values are shown in Fig. 7. Both  $F_{\text{CO}_2}$  and  $F_{\text{CH}_4}$  had a moderate seasonal variability showing higher fluxes in July and August. The monthly mean  $F_{\text{CO}_2}$  (standard deviation) was 0.19 (SD 0.31) in June, 0.34 (SD 0.32) in July, 0.44 (SD 0.32) in August and 0.41 (SD 0.24) μmol m<sup>-2</sup> s<sup>-1</sup> in September. The mean  $F_{\text{CO}_2}$  during the entire campaign was 0.36 (SD 0.31) μmol m<sup>-2</sup> s<sup>-1</sup>. The monthly mean fluxes are presented in Table 3.

The variability of  $F_{\text{CO}_2}$  was larger at nighttime compared to daytime during all months (Fig. 8, left panel). Performing a two-sample  $t$  test on  $F_{\text{CO}_2}$  during day and nighttime (09:00–15:00 and 21:00–03:00 local time, respectively) in different months, there is also a statistically significant difference ( $p < 0.05$ ) between the daytime and nighttime fluxes during June, July and August. In other words, during those months there was diurnal variation in the fluxes, the nighttime fluxes being higher. In September however, such variation did not exist. The mean nighttime  $F_{\text{CO}_2}$  (0.25 μmol m<sup>-2</sup> s<sup>-1</sup>) in June–September was 220



**Figure 5.** Environmental conditions during the campaign. The variables are shown as 30-minute average values, except for the precipitation data, which are shown as daily values. (a) Air temperature 2 m above river surface  $T_a$  (black) and water surface temperature  $T_{\text{surf}}$  (blue). (b) Deviation of the water temperature at 2.35 m / 2.05 m and 4.35 m / 4.05 m (bottom) from the surface temperature. (c) Atmospheric  $\text{CO}_2$  partial pressure  $p_{\text{CO}_2,a}$  (black) measured 0.4 m above the water surface and surface water  $\text{CO}_2$  partial pressure  $p_{\text{CO}_2,w}$  (blue). (d) Daily precipitation. (e) Wind speed  $U$ . (f) Water flow speed  $U_w$  (left, black) and discharge  $Q$  (right, blue). (g) Photosynthetically active radiation (PAR) at 0.30 m depth. Discharge was measured 11 km downstream. Precipitation was measured at the Tähtelä weather station.



**Figure 6.** Wind climatology during the campaign.

265 % of the mean daytime  $F_{\text{CO}_2}$  ( $0.55 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). The day–night difference in  $F_{\text{CO}_2}$  was significant when observing the entire campaign’s duration. Table 3 also contains the day and nighttime mean fluxes.

The monthly mean  $F_{\text{CH}_4}$  (standard deviation) was 2.7 (SD 2.4) (June), 4.8 (SD 3.9) (July), 4.3 (SD 5.1) (August) and 3.3 (SD 4.1)  $\text{nmol m}^{-2} \text{s}^{-1}$  (September). The mean  $F_{\text{CH}_4}$  during the campaign was 3.8 (SD 4.1)  $\text{nmol m}^{-2} \text{s}^{-1}$ . Contrary to  $F_{\text{CO}_2}$ , there was no statistically significant diurnal variation in  $F_{\text{CH}_4}$  during any month of the campaign (Fig. 8, right panel). The measured nighttime  $F_{\text{CH}_4}$  ( $3.3 \text{ nmol m}^{-2} \text{s}^{-1}$ ) in June–September was 80 % of the daytime flux ( $4.1 \text{ nmol m}^{-2} \text{s}^{-1}$ ).

270 There was a period of relatively high fluxes on 19–25 July. The daily mean  $\text{CO}_2$  fluxes reached  $0.55\text{--}0.7 \mu\text{mol m}^{-2} \text{s}^{-1}$  and  $\text{CH}_4$  fluxes  $7\text{--}12 \text{ nmol m}^{-2} \text{s}^{-1}$ . This period coincided with the discharge being constantly kept above  $100 \text{ m}^3\text{s}^{-1}$  and with the daily average winds being higher than during other times in July.

### 3.3 Relationship between the fluxes and environmental drivers

275 All possible combinations of the driving variables were tested, but here we present the five best models in each case. The models shown are statistically significant at a 95 % confidence level. There was intercorrelation between almost all driving variables, but the coefficient of determination was mostly low.

The best models for  $p\text{CO}_{2\text{w}}$  are similar at daily and weekly timescales (Table 4).  $p\text{CO}_{2\text{w}}$  was mainly driven by  $T_{\text{surf}}$ , PAR and  $U_{\text{w}}$ . Three of best daily models include  $U$ . The response to  $T_{\text{surf}}$  and  $U_{\text{w}}$  was positive, while it was negative for PAR. An exception is the negative response to  $U_{\text{w}}$  in the best weekly model. This model also includes precipitation as a driver.

$F_{\text{CO}_2}$ ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )				
	June	July	August	September
Total	$0.19 \pm 0.31$	$0.34 \pm 0.32$	$0.44 \pm 0.32$	$0.41 \pm 0.24$
Day	$0.00 \pm 0.34$	$0.31 \pm 0.32$	$0.24 \pm 0.28$	$0.37 \pm 0.23$
Night	$0.48 \pm 0.18$	$0.70 \pm 0.34$	$0.72 \pm 0.31$	$0.41 \pm 0.23$
Day–night difference	yes	yes	yes	no
$F_{\text{CH}_4}$ ( $\text{nmol m}^{-2} \text{s}^{-1}$ )				
	June	July	August	September
Total	$2.7 \pm 2.4$	$4.8 \pm 3.9$	$4.3 \pm 5.1$	$3.3 \pm 4.1$
Day	$3.2 \pm 2.4$	$4.8 \pm 3.6$	$4.7 \pm 6.0$	$3.5 \pm 4.7$
Night	$2.5 \pm 2.1$	$5.1 \pm 3.6$	$4.0 \pm 3.7$	$2.9 \pm 3.6$
Day–night difference	no	no	no	no

**Table 3.** Mean fluxes and their standard deviation in each month during the campaign and the overall mean fluxes. The mean fluxes and the standard deviation are also shown for day- and nighttime during each month. The day–night difference indicates whether there was a statistically significant difference in the fluxes between day and night.

280 The adjusted coefficient of determination  $R_{\text{adj}}^2$  was 0.407 and 0.516 for the best daily and best weekly model, respectively. The diurnal cycle of  $p\text{CO}_{2\text{w}}$  correlated mainly with  $T_{\text{surf}}$  with a negative response, as it appears in all the best five models. Four highest-ranking models also incorporate  $U_{\text{w}}$  as a driver with a negative response.  $R_{\text{adj}}^2$  is very high, 0.955, for the best model. Contrary to the daily and weekly means, only two models for the diurnal variability incorporated PAR as a driver and additionally, the response of  $p\text{CO}_{2\text{w}}$  to PAR was positive with the multiplier being close to 0.

285 The best regression model for the  $\text{CO}_2$  fluxes on a daily timescale contains  $\Delta p\text{CO}_2$ , PAR,  $U_{\text{w}}$  and  $U$  (Table 5). The coefficient between these variables and  $F_{\text{CO}_2}$  is positive except for PAR. Two models with the best second  $R_{\text{adj}}^2$  value includes also precipitation or  $T_{\text{surf}}$  as additional explanatory variables. The explanatory variables  $\Delta p\text{CO}_2, U_{\text{w}}$  and  $U$  appear in all of the five best models. The best model on a weekly timescale contains most of the selected environmental parameters, except PAR, which appears in the last three best models with a negative response. Four highest-ranking models also contain precipitation.

290  $R_{\text{adj}}^2$  was 0.621 for the best daily model and 0.928 for the best weekly model. The models' response to  $\Delta p\text{CO}_2, U_{\text{w}}$  and  $U$  was positive at both weekly and daily timescales, while the response to PAR was always negative. The models had variables response to  $T_{\text{surf}}$  and precipitation.

The diurnal variability in  $F_{\text{CO}_2}$  was mainly driven by  $\Delta p\text{CO}_2$  as it appears in all five models. Additionally,  $U$  is present in four out of five best models. The response of  $F_{\text{CO}_2}$  to these variables was negative.  $R_{\text{adj}}^2$  for the diurnal variability models was

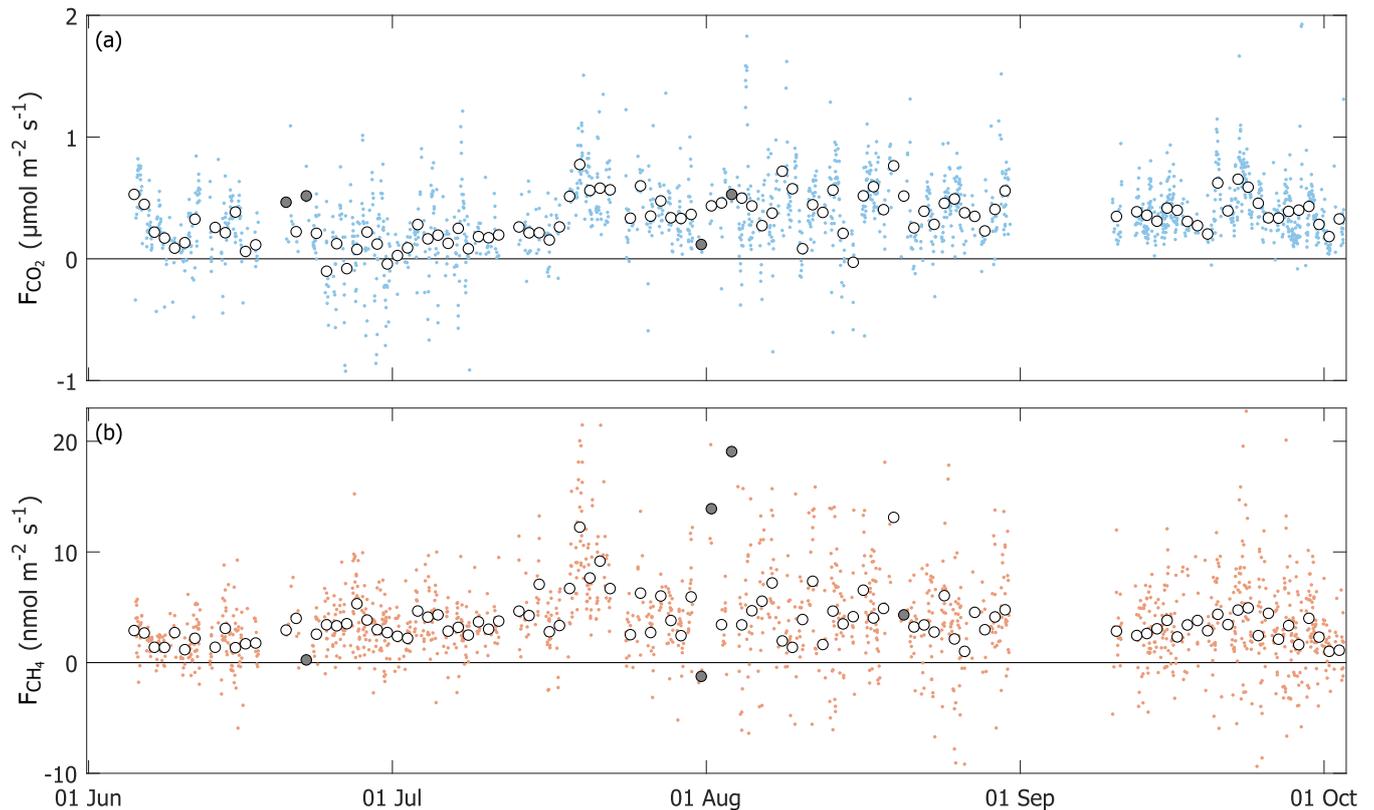
295 rather high, 0.89.

**Table 4.** Multivariate linear regression models between the partial pressure of CO<sub>2</sub> in water ( $p\text{CO}_{2\text{w}}$ , [ $\mu\text{atm}$ ]) and surface temperature ( $T_{\text{surf}}$ , [ $^{\circ}\text{C}$ ]), photosynthetically active radiation (PAR, [ $\mu\text{mol m}^{-2} \text{s}^{-1}$ ]), wind speed ( $U$ , [ $\text{m s}^{-1}$ ]), precipitation (prec, [ $\text{mm d}^{-1}$ ]) and water flow speed ( $U_{\text{w}}$ , [ $\text{m s}^{-1}$ ]) that give the highest value of  $R_{\text{adj}}^2$  at time scales (averaging periods) of 24 hours and 7 days, and averaged into a diurnal cycle. The Wilkinson notation is used in describing the combination of the variables. In the model formula, the unit of the intersection is  $\mu\text{atm}$  and the units of the variables' multipliers are  $\mu\text{atm}/[\text{unit of variable}]$ . Only statistically significant models are shown.

Combination	Formula	$R_{\text{adj}}^2$
1 day		
$T_{\text{surf}} + \text{PAR} + U_{\text{w}}$	$563 + 25.7T_{\text{surf}} - 1.18\text{PAR} + 586U_{\text{w}}$	0.407
$T_{\text{surf}} + \text{PAR} + \text{prec} + U_{\text{w}}$	$561 + 25.4T_{\text{surf}} - 1.14\text{PAR} + 49.3\text{prec} + 582U_{\text{w}}$	0.402
$T_{\text{surf}} + \text{PAR} + U_{\text{w}} + U$	$77 + 25.5T_{\text{surf}} - 1.19\text{PAR} + 561U_{\text{w}} - 2.62U$	0.392
$T_{\text{surf}} + \text{PAR} + \text{prec} + U_{\text{w}} + U$	$575 + 25.1T_{\text{surf}} - 1.14\text{PAR} + 59.8\text{prec} + 556U_{\text{w}} - 2.86U$	0.386
$T_{\text{surf}} + \text{PAR} + U$	$754 + 21.5T_{\text{surf}} - 1.27\text{PAR} - 10.6U$	0.306
7 days		
$T_{\text{surf}} + \text{PAR} + \text{prec} + U_{\text{w}}$	$545 + 37.9T_{\text{surf}} - 1.95\text{PAR} + 723\text{prec} - 87.8U_{\text{w}}$	0.516
$T_{\text{surf}} + \text{PAR} + U_{\text{w}}$	$563 + 38T_{\text{surf}} - 2.18\text{PAR} + 200U_{\text{w}}$	0.493
$T_{\text{surf}} + \text{PAR} + U_{\text{w}} + U$	$471 + 39T_{\text{surf}} - 2.12\text{PAR} + 245U_{\text{w}} + 28.3U$	0.452
$T_{\text{surf}} + \text{PAR}$	$686 + 31.6T_{\text{surf}} - 2.12\text{PAR}$	0.443
$T_{\text{surf}} + \text{PAR} + \text{prec}$	$674 + 28.7T_{\text{surf}} - 1.83\text{PAR} + 514\text{prec}$	0.433
Diurnal		
$T_{\text{surf}} + \text{PAR} + U_{\text{w}} + U$	$0.0465 - 64.6T_{\text{surf}} + 0.116\text{PAR} - 263U_{\text{w}} - 5.33U$	0.955
$T_{\text{surf}} + \text{PAR} + U_{\text{w}}$	$0.0599 - 69.6T_{\text{surf}} + 0.0929\text{PAR} - 256U_{\text{w}}$	0.951
$T_{\text{surf}} + U_{\text{w}} + U$	$0.0612 - 97.1T_{\text{surf}} - 96U_{\text{w}} + 7.32U$	0.901
$T_{\text{surf}} + U_{\text{w}}$	$0.0337 - 101T_{\text{surf}} - 26.7U_{\text{w}}$	0.887
$T_{\text{surf}}$	$0.0313 - 107T_{\text{surf}}$	0.881

**Table 5.** Multivariate linear regression models between CO<sub>2</sub> fluxes and surface temperature ( $T_{\text{surf}}$ , [°C]), partial pressure of CO<sub>2</sub> in water ( $p\text{CO}_{2\text{w}}$ , [µatm]), photosynthetically active radiation (PAR, [µmol m<sup>-2</sup> s<sup>-1</sup>]), wind speed ( $U$ , [m s<sup>-1</sup>]), precipitation (prec, [mm d<sup>-1</sup>]) and water flow speed ( $U_w$ , [m s<sup>-1</sup>]) that give the highest value of  $R_{\text{adj}}^2$  at time scales (averaging periods) of 24 hours and 7 days, and averaged into a diurnal cycle. The Wilkinson notation is used in describing the combination of the variables. In the model formula, the unit of the intersection is µmol m<sup>-2</sup> s<sup>-1</sup> and the units of the variables' multipliers are µmol m<sup>-2</sup> s<sup>-1</sup>/[unit of variable]. Only statistically significant models are shown.

Combination	Formula	$R_{\text{adj}}^2$
1 day		
$\Delta p\text{CO}_2 + \text{PAR} + U_w + U$	$-0.207 + 0.000665 \Delta p\text{CO}_2 - 0.000351 \text{PAR} + 0.499 U_w + 0.091 U$	0.616
$\Delta p\text{CO}_2 + \text{PAR} + \text{prec} + U_w + U$	$-0.207 + 0.000661 \Delta p\text{CO}_2 - 0.00033 \text{PAR} + 0.0285 \text{prec} + 0.488 U_w + 0.0911 U$	0.613
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{PAR} + U_w + U$	$-0.215 + 0.00114 T_{\text{surf}} + 0.000653 \Delta p\text{CO}_2 - 0.000385 \text{PAR} + 0.491 U_w + 0.0917 U$	0.608
$\Delta p\text{CO}_2 + U_w + U$	$-0.292 + 0.000725 \Delta p\text{CO}_2 + 0.405 U_w + 0.101 U$	0.607
$T_{\text{surf}} + \Delta p\text{CO}_2 + U_w + U$	$-0.224 - 0.00465 T_{\text{surf}} + 0.00075 \Delta p\text{CO}_2 + 0.478 U_w + 0.0945 U$	0.605
7 days		
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{prec} + U_w + U$	$-0.325 - 0.0488 T_{\text{surf}} + 0.000478 \Delta p\text{CO}_2 - 2.91 \text{prec} + 8.90 U_w + 0.0495 U$	0.931
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{prec} + U_w$	$-0.2 - 0.0562 T_{\text{surf}} + 0.000448 \Delta p\text{CO}_2 - 3.17 \text{prec} + 9.83 U_w$	0.925
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{PAR} + \text{prec} + U_w$	$-0.127 - 0.0429 T_{\text{surf}} + 0.000329 \Delta p\text{CO}_2 - 0.000627 \text{PAR} - 2.63 \text{prec} + 8.61 U_w$	0.917
$\Delta p\text{CO}_2 + \text{PAR} + \text{prec} + U_w + U$	$-0.16 + 0.000188 \Delta p\text{CO}_2 - 0.00175 \text{PAR} - 0.757 \text{prec} + 3.67 U_w + 0.076 U$	0.867
$\Delta p\text{CO}_2 + \text{PAR} + U_w + U$	$-0.0676 + 0.000207 \Delta p\text{CO}_2 - 0.00156 \text{PAR} + 2.63 U_w + 0.0672 U$	0.862
Diurnal		
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{PAR} + U_w + U$	$0.0193 - 0.17 T_{\text{surf}} - 0.00637 \Delta p\text{CO}_2 + 0.000426 \text{PAR} - 0.976 U_w - 0.105 U$	0.890
$\Delta p\text{CO}_2 + \text{PAR} + U_w + U$	$0.0191 - 0.00411 \Delta p\text{CO}_2 + 0.000431 \text{PAR} - 0.881 U_w - 0.156 U$	0.889
$\Delta p\text{CO}_2 + U$	$0.0189 - 0.00204 \Delta p\text{CO}_2 - 0.169 U$	0.884
$T_{\text{surf}} + \Delta p\text{CO}_2 + U$	$0.019 - 0.131 T_{\text{surf}} - 0.00367 \Delta p\text{CO}_2 - 0.138 U$	0.884
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{PAR} + U_w$	$0.0196 - 0.401 T_{\text{surf}} - 0.00999 \Delta p\text{CO}_2 - 0.000407 \text{PAR} + 0.0193 U_w - 0.14 U$	0.884



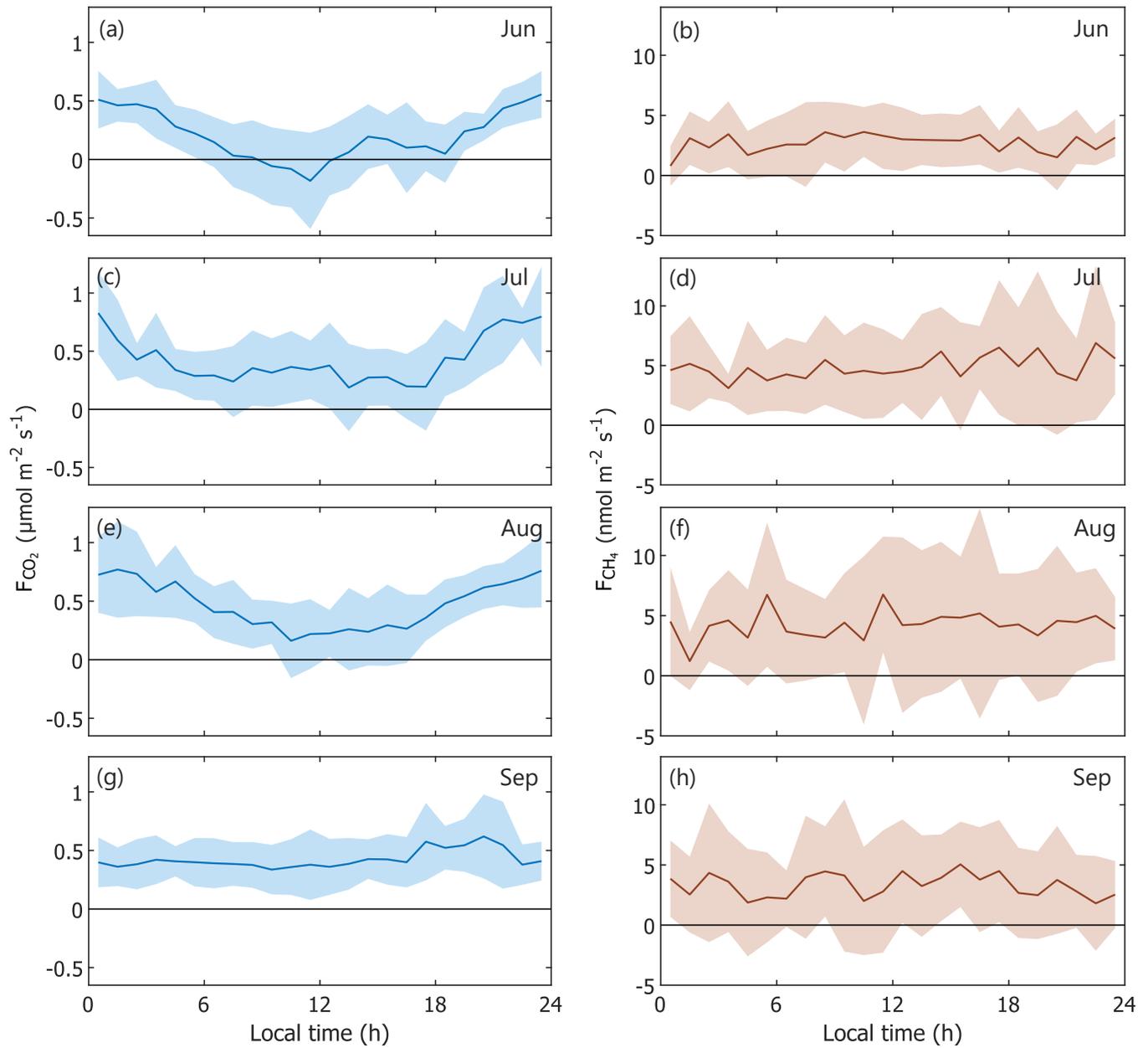
**Figure 7.** Time series of the CO<sub>2</sub> (top) and CH<sub>4</sub> flux (bottom). The dots indicate the 30-minute values and the circles indicate the daily averages. Fluxes are quality-controlled. The daily fluxes are drawn with a dark circle if the day contained only three or less 30-minute fluxes.

The best models for CH<sub>4</sub> fluxes on both daily and weekly timescales all contain  $T_{\text{surf}}$  and the fluxes' response to  $T_{\text{surf}}$  is positive. The best models on a daily scale additionally contain  $U$ . On the weekly scale, most of the best models also include PAR.  $R_{\text{adj}}^2$  is only 0.19–0.22 on a daily timescale due to the large scatter in the data. On a weekly scale,  $R_{\text{adj}}^2$  is high because the amount of weekly data was small. The diurnal variability was mainly driven by  $T_{\text{surf}}$  with a positive response, but  $R_{\text{adj}}^2$  is very low, only 0.12 in the best model.

## 4 Discussion

### 4.1 Challenges of EC flux measurements over river

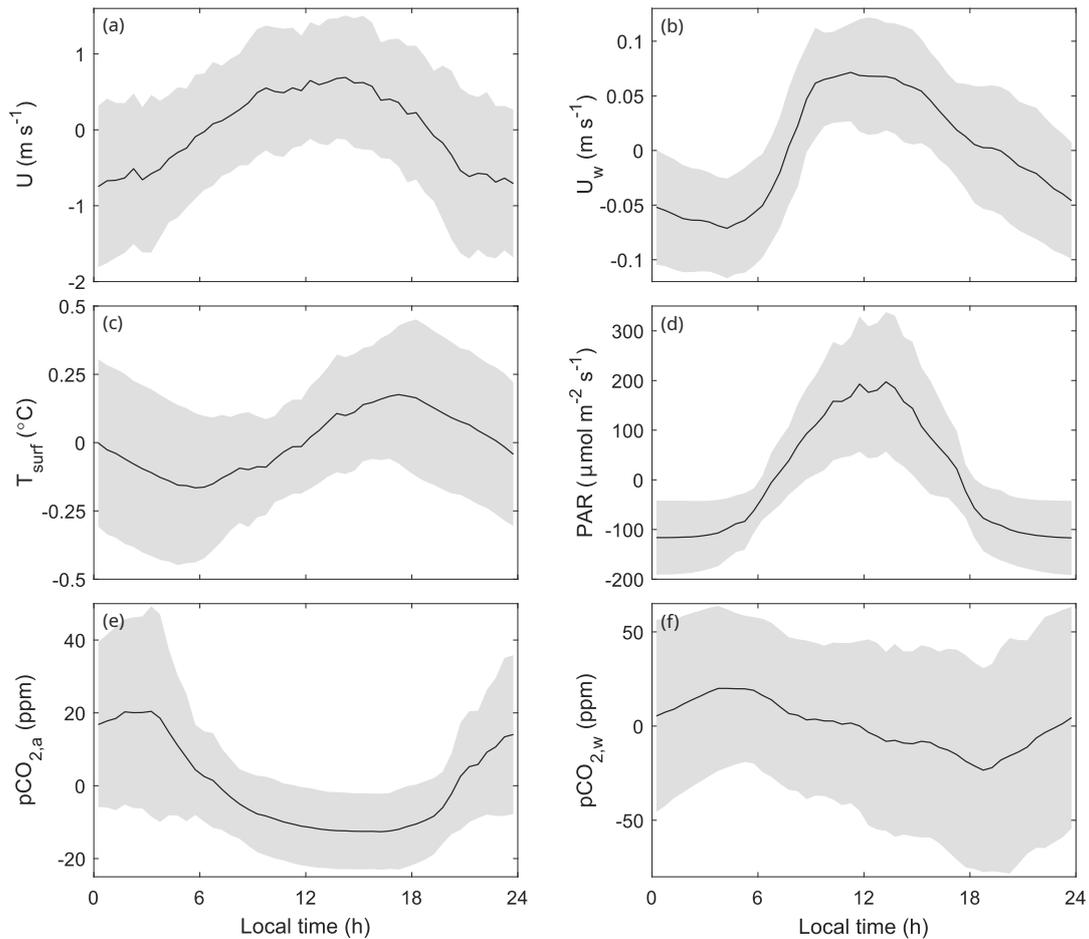
The EC technique is widely used for continuous and long-term monitoring of energy and gas exchange between land ecosystems (forest, wetland, arable land, grassland) and atmosphere (Baldocchi, 2003). The method has been applied only recently to inland aquatic ecosystems, and at the moment there is no comprehensive network of long-term EC sites covering different latitude and climatic zones, and water bodies characteristics. Most of the previous EC studies over inland water bodies have



**Figure 8.** Diurnal variation of of CO<sub>2</sub> flux (a, c, e, g) and CH<sub>4</sub> flux (b, d, f, h) in different months, averaged in 1-hour bins. The line and the shaded area indicate the mean flux and its standard deviation.

**Table 6.** Multivariate linear regression models between CH<sub>4</sub> fluxes and surface temperature ( $T_{\text{surf}}$ , [°C]), partial pressure of CO<sub>2</sub> in water ( $p\text{CO}_{2\text{w}}$ , [µatm]), photosynthetically active radiation (PAR, [µmol m<sup>-2</sup> s<sup>-1</sup>]), wind speed ( $U$ , [m s<sup>-1</sup>]), precipitation (prec, [mm d<sup>-1</sup>]) and water flow speed ( $U_w$ , [m s<sup>-1</sup>]) that give the highest value of  $R_{\text{adj}}^2$  at time scales (averaging periods) of 24 hours and 7 days, and averaged into a diurnal cycle. The Wilkinson notation is used in describing the combination of the variables. In the model formula, the unit of the intersection is nmol m<sup>-2</sup> s<sup>-1</sup> and the units of the variables' multipliers are nmol m<sup>-2</sup> s<sup>-1</sup>/[unit of variable]. Only statistically significant models are shown.

Combination	Formula	$R_{\text{adj}}^2$
1 day		
$T_{\text{surf}} + U$	$-0.211 + 0.157 T_{\text{surf}} + 0.599 U$	0.220
$T_{\text{surf}} + \text{PAR} + U$	$-0.2 + 0.17 T_{\text{surf}} - 0.00126 \text{PAR} + 0.58 U$	0.206
$T_{\text{surf}} + \text{prec} + U$	$-0.21 + 0.157 T_{\text{surf}} - 0.0261 \text{prec} + 0.599 U$	0.204
$T_{\text{surf}} + U_w + U$	$-1.72 + 0.186 T_{\text{surf}} + 7.01 U_w + 0.634 U$	0.201
$T_{\text{surf}} + \Delta p\text{CO}_2 + U$	$-0.61 + 0.139 T_{\text{surf}} + 0.00154 \Delta p\text{CO}_2 + 0.591 U$	0.189
7 days		
$T_{\text{surf}} + \text{PAR} + U_w + U$	$1.15 + 0.408 T_{\text{surf}} - 0.0162 \text{PAR} - 17.1 U_w + 0.507 U$	0.875
$T_{\text{surf}} + \text{PAR} + U_w$	$2.81 + 0.393 T_{\text{surf}} - 0.0178 \text{PAR} - 17.8 U_w$	0.792
$T_{\text{surf}} + \Delta p\text{CO}_2 + U$	$-1.66 + 0.20 T_{\text{surf}} + 0.00402 \Delta p\text{CO}_2 + 0.497 U$	0.768
$T_{\text{surf}} + \Delta p\text{CO}_2 + \text{PAR}$	$2.30 + 0.279 T_{\text{surf}} - 0.00156 \Delta p\text{CO}_2 - 0.0139 \text{PAR}$	0.759
$T_{\text{surf}} + \text{PAR} + U$	$0.304 + 0.292 T_{\text{surf}} - 0.0119 \text{PAR} + 0.376 U$	0.751
Diurnal		
$T_{\text{surf}} + \text{PAR}$	$-0.0244 + 1.69 T_{\text{surf}} + 0.000098 \text{PAR}$	0.116
$T_{\text{surf}} + \Delta p\text{CO}_2$	$-0.0247 + 2.41 T_{\text{surf}} + 0.0121 \Delta p\text{CO}_2$	0.114
$T_{\text{surf}} + U_w$	$-0.0247 + 1.35 T_{\text{surf}} + 2.44 U_w$	0.113
$T_{\text{surf}} + U$	$-0.0239 + 1.56 T_{\text{surf}} + 0.219 U$	0.111
$T_{\text{surf}}$	$-0.0245 + 1.92 T_{\text{surf}}$	0.102



**Figure 9.** Mean diurnal cycles of the flux drivers, calculated by first subtracting the daily mean from each individual day. The line and the shaded area mark the mean and standard deviation. (a) Wind speed. (b) Flow speed. (c) Surface temperature. (d) Photosynthetically active radiation at 0.30 m depth. (e).  $\text{CO}_2$  mixing ratio in air. (f)  $\text{CO}_2$  mixing ratio in surface water.

focused on lakes and on their water-atmosphere energy exchange, while only few studies have reported direct EC fluxes of  $\text{CO}_2$  and  $\text{CH}_4$  over lakes (Mammarella et al., 2015; Czikowsky et al., 2018; Eugster et al., 2020; Golub et al., 2023). So far, only one study has reported  $\text{CO}_2$  fluxes measured by EC technique over river (Huotari et al., 2013). While land-based EC flux measurements and data processing chains are well established (Sabbatini et al., 2018; Nemitz et al., 2018), standard EC data processing steps are not always applicable for measurements over inland water bodies. Fluxes are often smaller in magnitude than those typically found over land and the reduced turbulent mixing over a smooth water surface may lead to further limitations during calm or moderate wind conditions (Spank et al., 2020), when the advection of gases from land also poses a problem for the EC flux measurements, not representing the surface gas exchange in these cases.

315 Standard low turbulence filtering criteria based on friction velocity or standard deviation of vertical component of wind  
velocity are not recommended for EC fluxes over lakes and rivers, as the wind-shear-generated turbulence is one of the main  
driver of gas exchange at water–air interface. Here, we have proposed the method of dividing the 30-minute intervals into  
shorter 5-minute sub-intervals, which reveals how short term changes in wind directions may contaminate the measured CO<sub>2</sub>  
signal, affecting the quality of measured 30-minutes fluxes (Fig. A2). Removing these situations when the flux signal originates  
320 from land makes the measured flux closer to an unbiased estimate of the gas exchange between the water surface and the  
atmosphere.

Few different approaches have been proposed for filtering low turbulence and/or advection-dominated conditions, based on  
e.g. a minimum threshold value for the atmospheric stability (Czikowsky et al., 2018), a maximum threshold for the standard  
deviation of atmospheric CO<sub>2</sub> mixing ratio (Erkkilä et al., 2018), or thresholds for the trend  $d\chi/dt$  and for the horizontal  
325 turbulent flux  $\overline{u'\chi'}$  of the compound (Blomquist et al., 2012). The choice of threshold values is a mostly empirical, partly  
arbitrary and often site-specific choice for e.g. stability, friction velocity or gas mixing ratio. Despite our new wind sub-interval  
filtering method, we still had to implement a screening based on maximum threshold values of standard deviation of gas mixing  
ratios. This demonstrates the challenges in and importance of finding the correct criteria for the data screening.

#### 4.2 Magnitude and temporal dynamics of fluxes

330 So far, only Huotari et al. (2013) have reported EC CO<sub>2</sub> fluxes over a river. Measurements have been carried out for about one  
month in summer 2009 at the River Kymijoki (southern Finland), which is wider than River Kitinen and has a mean annual  
discharge 2.7 times as large as that of Kitinen, resulting in higher water flow velocity ranging between 0.15 and 1.17 m s<sup>-1</sup>,  
with a mean value of 0.66 m s<sup>-1</sup> (Huotari et al., 2013). The mean  $F_{\text{CO}_2}$  over Kymijoki during their measurements was  $0.94 \pm$   
 $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ , 2.5 times as high as  $F_{\text{CO}_2}$  over Kitinen during the KITEX campaign. Huotari et al. (2013) attributed changes  
335 in the measured flux to changes in  $p\text{CO}_2$  in the water, which in turn was negatively correlated with discharge. Contrary to this  
study, Huotari et al. (2013) did not detect any significant diurnal cycle in  $F_{\text{CO}_2}$ . They measured  $p\text{CO}_2$  to be approximately  
600–1000  $\mu\text{atm}$ , which is less than what was measured during the KITEX campaign. The larger  $F_{\text{CO}_2}$  in Kymijoki is then  
likely due to the larger water flow velocity, enhancing the efficiency of gas exchange at the air–water interface.

Diurnal changes in  $p\text{CO}_2$  in a boreal lake have been linked with photosynthetic activity and ecosystem respiration in the  
340 water (Åberg et al., 2010) and that is likely the case in a boreal river as well. Although subsaturation of dissolved CO<sub>2</sub>  
relative to the atmosphere was not detected at the Kitinen platform, it is still possible that lateral gradients exist in the  $p\text{CO}_{2\text{w}}$   
due to higher photosynthesis close to the river banks, and that during the day, some parts of the river could be subsequently  
subsaturated with CO<sub>2</sub>. The negative correlation found between  $p\text{CO}_{2\text{w}}$  and PAR in River Kitinen supports this hypothesis.

Some earlier studies on boreal and arctic rivers have reported CO<sub>2</sub> fluxes measured by floating chambers. Although they  
345 represent different spatial and temporal scales, the mean values of such fluxes can still be compared to the magnitude of EC  
fluxes from our study. Huttunen et al. (2002) carried out chamber measurements at the hydroelectric reservoir Porttipahta,  
which is 75 km upstream of the KITEX experiment site. The measurements were conducted in 1995 when the reservoir had  
existed for 28 years. They detected fluxes which were relatively close (within 50 %–150 %) to our observations, the mean

$F_{\text{CO}_2}$  being  $0.57 \mu\text{mol m}^{-2} \text{s}^{-1}$ . Silvennoinen et al. (2008) measured a mean  $\text{CO}_2$  flux of  $5.2 \mu\text{mol m}^{-2} \text{s}^{-1}$  from the small, eutrophic River Temmesjoki in central Finland during summer. The mean  $F_{\text{CO}_2}$  from the River Kolyma main stem in eastern Siberia was  $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ , relatively close to that of Kitinen (Denfeld et al., 2013). Campeau et al. (2014) determined  $F_{\text{CO}_2}$  from boreal streams and rivers (Strahler orders 1–6) in Quebec in Canada to be  $0.85 \mu\text{mol m}^{-2} \text{s}^{-1}$ . Other studies have revealed substantially larger emissions of  $\text{CO}_2$ , such as  $2.0 \mu\text{mol m}^{-2} \text{s}^{-1}$  on River Yukon in Alaska (Striegl et al., 2012) and  $6.2 \mu\text{mol m}^{-2} \text{s}^{-1}$  on different-sized western Siberian river systems in Russia during summer ( $6.3 \mu\text{mol m}^{-2} \text{s}^{-1}$  if only areas without permafrost are considered) (Serikova et al., 2018). None of these studies focused on diurnal differences in the emissions.

Recently, differences in the day and nighttime  $F_{\text{CO}_2}$  over rivers have been observed globally (Gómez-Gener et al., 2021) and in European streams and small rivers (Attermeyer et al., 2021). Floating chamber measurements may be biased towards daytime measurements. In this aspect, EC measurements fill the need for continuous measurements with higher temporal resolution. Indeed, our findings show that sampling only during the day would give a considerably underestimated value of  $F_{\text{CO}_2}$  and a slight overestimation of  $F_{\text{CH}_4}$ , the average daytime fluxes being 220 % and 80 % of the nighttime fluxes for  $\text{CO}_2$  and  $\text{CH}_4$ , respectively. Continuous sampling is therefore recommended for unbiased averaged flux estimates.

Both Gómez-Gener et al. (2021) and Attermeyer et al. (2021) found that the day–night difference in  $F_{\text{CO}_2}$  was mainly driven by a diurnal change in water-side  $p\text{CO}_2$ , which results from daytime photosynthetic fixation of  $\text{CO}_2$ . The day–night difference in  $F_{\text{CO}_2}$  observed by Attermeyer et al. (2021) using drifting chambers was on average  $0.14 \mu\text{mol m}^{-2} \text{s}^{-1}$ . Our study showed a considerably larger difference, potentially suggesting a difference in streams and rivers as gas emitters. This difference can be partly attributed to diurnal differences in  $p\text{CO}_2$  as is shown in the diurnal analysis for  $F_{\text{CO}_2}$ , following the result by Rocher-Ros et al. (2019) that the magnitude of gas evasion is controlled by the supply of the said gas in the river.

Boreal rivers are typically supersaturated with  $\text{CH}_4$  with  $p\text{CH}_4$  ranging several orders of magnitude. For instance, Campeau and del Giorgio (2014) observed a median  $p\text{CH}_4$  of  $123 \mu\text{atm}$  in rivers of stream orders 5–6 in Quebec and a median of Hutchins et al. (2019)  $129 \mu\text{atm}$  with streams and rivers of orders 1–7. In Alaska, partial pressures of  $4 \mu\text{atm}$  in a river of stream order 4 (Crawford et al., 2013) and  $8.4 \mu\text{atm}$  in the Yukon River, decreasing with increasing stream order (Striegl et al., 2012), have been reported.

No earlier studies on  $\text{CH}_4$  emissions from rivers have been previously conducted with EC. Consequently, comparison to similar studies cannot be done. Still,  $\text{CH}_4$  emissions from boreal rivers have been measured with floating chambers. Huttunen et al. (2002) measured  $F_{\text{CH}_4}$  to be  $2.6 \text{nmol m}^{-2} \text{s}^{-1}$  from the boreal reservoir Porttipahta, which is very close to the mean value of  $3.9 \text{nmol m}^{-2} \text{s}^{-1}$  measured during this field campaign. Silvennoinen et al. (2008) reported a larger emission of  $F_{\text{CH}_4}$  of  $63 \text{nmol m}^{-2} \text{s}^{-1}$  from the Estuary of Temmesjoki River in the shallow Liminganlahti Bay in Finland. Other earlier studies report similar  $\text{CH}_4$  flux magnitude ( $94 \text{nmol m}^{-2} \text{s}^{-1}$ ) as averaged value from different stream orders and seasons in two boreal regions in Quebec (Campeau et al., 2014).

Sieczko et al. (2020) show that methane emissions from lakes can indeed have a diel cycle and that the higher daytime emissions are likely caused by a higher wind speed and the occurrence of ebullition. In our study, there were no significant differences between daytime and nighttime  $F_{\text{CH}_4}$ , but we found higher daily and weekly mean flux in July when we recorded

the highest values of PAR and water temperature. Similarly, Rovelli et al. (2021) found no diurnal difference in CH<sub>4</sub> emissions  
385 from a river which they attribute to mixing in the river.

### 4.3 Drivers of $p\text{CO}_{2\text{w}}$

Although many of the previous studies have been conducted in streams, i.e. with a lower Strahler order, it is likely that the  
same processes that drive the flux apply in rivers as well but with a different relative importance (Hotchkiss et al., 2015). The  
models that contain  $p\text{CO}_{2\text{w}}$  explain a large part of the variability in  $F_{\text{CO}_2}$ , similarly to what has been found in other rivers  
390 (e.g., Rocher-Ros et al., 2020).

The source of CO<sub>2</sub> in the river can be the soil catchment, where the CO<sub>2</sub> is flushed as either dissolved organic or inorganic  
carbon or directly injected as CO<sub>2</sub> (Hotchkiss et al., 2015), or it can be the result of aquatic ecosystem metabolism taking place  
in the river itself (Hall et al., 2016). The daily and weekly means of  $p\text{CO}_{2\text{w}}$  in Kitinen were controlled mainly by  $T_{\text{surf}}$  and  
PAR with a positive and negative response, respectively. They are the drivers of the net ecosystem exchange which consists  
395 of the assimilation of CO<sub>2</sub> by photosynthesis and release of CO<sub>2</sub> by respiration. The uptake of CO<sub>2</sub> in a river is controlled  
by available light and the amount of respiration by temperature (Lynch et al., 2010). Temperature also affects the composition  
of dissolved inorganic carbon in the river (Spank et al., 2020) and changes the CO<sub>2</sub> solubility (Chien et al., 2018). Terrestrial  
photosynthesis and respiration potentially act at different temporal scales than in the river, in addition to which the runoff-  
induced time delay further complicates the comparison between  $p\text{CO}_{2\text{w}}$  and terrestrial cycles. Still, the dependence of CO<sub>2</sub> on  
400 both  $T$  and PAR is evident on both daily and weekly timescales which suggests that processes taking place at both time scales  
could be important. In the daily variability, the importance of radiation was less pronounced and the models have generally low  
values of  $R_{\text{adj}}^2$ . The underlying reason is the time delay between the forcing and  $p\text{CO}_{2\text{w}}$ , as can be seen in panels (d) and (f) in  
Fig. 9.

Precipitation is the key factor in runoff, however, the measured precipitation at one point might not be completely repre-  
405 sentative of the total precipitation over the entire watershed. Nevertheless, the precipitation appears in some daily and weekly  
models for  $p\text{CO}_{2\text{w}}$ , likely indicating that both local and terrestrial sources of CO<sub>2</sub> affect  $p\text{CO}_{2\text{w}}$  in Kitinen, but their relative  
contribution is unknown.

Liu and Raymond (2018) found a negative correlation between  $p\text{CO}_{2\text{w}}$  and discharge in stream order up to 4 and no corre-  
lation in streams of order 5. Campeau and del Giorgio (2014) found a negative correlation between  $U_{\text{w}}$  and  $p\text{CO}_{2\text{w}}$ , using data  
410 from stream orders 1–6. Small rivers are more prone to evade than transport gases in which case the correlation is negative as  
higher flow velocities enhance mixing in the river (Liu and Raymond, 2018). Positive correlation implies an added advection  
of CO<sub>2</sub> in the river and possibly added flushing of soils. The different sign of  $U_{\text{w}}$  in the models at different time scales reveals  
a pattern where the short-term forcing causes an evasion of CO<sub>2</sub> from the river while in the long term, increased flow and thus  
increased discharge increases the amount of CO<sub>2</sub>. As a middle-sized river, the River Kitinen falls in the intermediate range  
415 where outgassing is controlled by both water flow and wind and the relative importance of  $U_{\text{w}}$  on gas dynamics is smaller than  
in small rivers (Alin et al., 2011). This is supported also by Guseva et al. (2021), who found that bottom-generated turbulence

was the dominant factor in controlling near-surface turbulence during 40% of the time during the KITEX campaign, less often than wind-created turbulence.

The response of  $p\text{CO}_{2w}$  to  $U$  was varying in the best daily, weekly and diurnal models. Scofield et al. (2016) found a negative correlation between  $p\text{CO}_{2w}$  and wind speed in the large River Negro in Amazon which they attribute to the importance of the wind speed controlling the outgassing. However, our results indicate that the significance of  $U$  as a driver of  $p\text{CO}_{2w}$  in Kitinen is limited as it appears in three of the best daily models, only one weekly model, and two diurnal models. The two variables can also exhibit intercorrelation but not necessarily causality. For example, high daily wind speeds coincided with low daily  $p\text{CO}_{2w}$  values during early summer and late autumn but were caused by different factors: atmospheric dynamics vs. high dilution by precipitation and low respiration due to low water temperature.

#### 4.4 Drivers of fluxes

It is evident from Table 5 that the main drivers of  $\text{CO}_2$  fluxes in our study are  $\Delta p\text{CO}_2$ ,  $U_w$  and  $U$  on the daily and weekly timescales and they also act as drivers of the diurnal cycle in  $F_{\text{CO}_2}$ . The dependence on  $p\text{CO}_{2w}$  is expected and has been shown in many earlier studies (e.g., Hutchins et al., 2020). Interestingly, although temperature and radiation have been shown to control the metabolism in rivers (Rocher-Ros et al., 2020, e.g.,) and they are strongly related to the patterns in  $p\text{CO}_{2w}$ , these variables do not emerge as clearly as drivers of  $F_{\text{CO}_2}$ . Their effect is likely shadowed by the more pronounced effect of  $\Delta p\text{CO}_2$ ,  $U_w$  and  $U$ . Additionally, the response of  $F_{\text{CO}_2}$  to  $\Delta p\text{CO}_2$  is negative in the diurnal variability, opposite to what would be expected based on the diurnal cycle of the  $\text{CO}_2$  fluxes. This can be caused by the spatial heterogeneity of  $p\text{CO}_{2w}$  in the river but also by  $\Delta p\text{CO}_2$  and  $F_{\text{CO}_2}$  not peaking at the same time during the day.

Liu and Raymond (2018) showed in their study a dependence of  $F_{\text{CO}_2}$  on the discharge and thus  $U_w$ , which can be explained by either  $U_w$  directly increasing mixing in the river by means of bottom friction (Liu et al., 2017), or by flushing of surrounding soils, similarly as in the relationship between  $U_w$  and  $p\text{CO}_{2w}$ . As  $U_w$  appears more in daily than weekly models and the flushing is a slower process than mixing in the river, it is likely the enhanced mixing that contributes to the regression. Precipitation works similarly as  $U_w$  that it enhances mixing in the river, particularly the surface water, and increases the runoff in the watershed. On the other hand, the locally-observed precipitation does not incorporate all of the precipitation events over the watershed and thus precipitation is not highly important as a driver.

$U$  is known to control the efficiency of air-water gas exchange by means of surface shear generated turbulence in lakes and ocean, and it has been observed in earlier studies to be an important factor also over large rivers (e.g., Alin et al., 2011; Hall and Ulseth, 2019). Our results show  $U$  to be a significant driver of  $F_{\text{CO}_2}$  at sub-daily, daily and weekly timescales.

For lakes, the  $\text{CH}_4$  production in sediments depends exponentially on the sediment temperature beside the  $\text{O}_2$  and  $\text{CO}_2$  concentrations (e.g. Stepanenko et al., 2016). Produced  $\text{CH}_4$  is then transported towards the surface by diffusion and turbulence being prone to oxidation, which depends on the  $\text{O}_2$  concentration in the water column. Some fraction of  $\text{CH}_4$  flux may evolve by ebullition avoiding oxidation. It was not tried to identify ebullition in the EC data. However, the overall magnitude of  $\text{CH}_4$  fluxes was low which does not support the possibility of ebullition.

450 Water temperature is the most important driver of  $\text{CH}_4$  emissions (Yvon-Durocher et al., 2014; Stanley et al., 2016) and it is clearly visible also in all best models (Table 6). In addition, the wind speed can have a quick physical forcing on either water-column processes (vertical mixing) or directly on the surface flux (gas transfer coefficient) and thus it appears as the important driver also at the daily and weekly scale. Water temperature emerged also as the main driver of the diurnal variability. However, it must be noted that  $F_{\text{CH}_4}$  did not exhibit any statistically significant daily variability. This is reflected in very low values of  
455  $R_{\text{adj}}^2$ .

Rovelli et al. (2021) describes  $\text{CH}_4$  dynamics for small streams by following:  $\text{CH}_4$  shows a nonlinear response to seasonal changes in discharge and is predominantly produced in the stream bed. Once released from the bed, outgassing of  $\text{CH}_4$  at the surface and flow-driven dilution occur far more rapidly than biological methane oxidation. In lakes,  $\text{CH}_4$  is likewise borne from biological processes in the sediment and then transported mostly vertically (e.g. Stepanenko et al., 2016). As a regulated river,  
460 the characteristics of River Kitinen are between small streams and lakes. Although  $p\text{CH}_{4\text{w}}$  and sediment temperature were not measured during the campaign nor were all the drivers of  $\text{CH}_4$  production, consumption, anaerobic metabolism and ecosystem energetics (like quality of organic matter, nutrients; see Stanley et al. (2016)), the multivariate regression analysis reveals the combined biotic and abiotic features of  $\text{CH}_4$  flux drivers. The results described above corroborate the general picture of  $\text{CH}_4$  production and transport.

465 Campeau and del Giorgio (2014) and Hutchins et al. (2019) found a positive correlation between  $p\text{CO}_{2\text{w}}$  and  $p\text{CH}_{4\text{w}}$  in streams and rivers in boreal Canada. As we did not measure  $p\text{CH}_{4\text{w}}$ , we cannot analyse this correlation in River Kitinen, but we included  $\Delta p\text{CO}_2$  as a variable in the multivariate analysis. It appears as a driver in one daily, two weekly and one diurnal model but with a variable sign in response. This ambiguity can be explained simply by the overall weak indirect linkage between  $p\text{CO}_{2\text{w}}$ ,  $p\text{CH}_{4\text{w}}$  and the  $\text{CH}_4$  flux. Still, the positive correlation with  $T_{\text{surf}}$  and negative with PAR, the most significant  
470 drivers of  $p\text{CO}_{2\text{w}}$ , could suggest a linkage between  $p\text{CO}_{2\text{w}}$  and  $p\text{CH}_{4\text{w}}$ .

Finally, we found a negative correlation between PAR and  $F_{\text{CH}_4}$ , mainly in the weekly means. The correlation at the daily scale is weak as PAR exists as a variable in only one of the models. Additionally, while the magnitude of  $F_{\text{CH}_4}$  was at its highest in late July and early August, PAR peaked in early July which, in turn, reduces the daily correlation. PAR and  $\text{CH}_4$  flux have been found to correlate positively in stratified lakes due to photosynthesis-driven oxic methane production (Günthel et al.,  
475 2020) and light-dependent aerobic methane oxidation (Oswald et al., 2015). These processes are therefore likely non-important in River Kitinen.

## 5 Conclusions

In this study, we have reported results from a four months field campaign over a boreal river, including the longest  $\text{CO}_2$  and the first ever  $\text{CH}_4$  continuous flux data measured on a river by using the eddy covariance method. On average, the river was a net  
480 source of  $\text{CO}_2$  and  $\text{CH}_4$  to the atmosphere. The  $\text{CO}_2$  fluxes shown clear seasonal variation, reaching the maximum monthly value of  $0.44 \pm 0.32 \mu\text{mol m}^{-2} \text{s}^{-1}$  in August, and the minimum of  $0.19 \pm 0.31 \mu\text{mol m}^{-2} \text{s}^{-1}$  in June. We found a statistically significant difference ( $p < 0.05$ ) between the daytime and nighttime fluxes during June, July and August of 0.48, 0.39 and

0.48  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , respectively. In addition, we found that the main physical drivers of  $p_{\text{CO}_2, \text{w}}$  were  $T_{\text{surf}}$  and PAR. The  $\text{CO}_2$  fluxes were mainly driven by  $\Delta p_{\text{CO}_2}$  and  $U_{\text{w}}$  while the main drivers for  $\text{CH}_4$  fluxes were  $T_{\text{surf}}$  and  $U$ . Similar additional  
485 studies in rivers are needed as the EC observations complement chamber observations providing information at the ecosystem scale but with a better temporal resolution. As rivers represent spatially small ecosystems with limited fetches, special care is required in the source area analysis by footprint modelling and filtering out the contribution from the land. This is a prerequisite for the accurate detection of e.g. diurnal cycles in fluxes. The more detailed observation of the wind direction fluctuations has appeared to be an effective tool for identifying and removing of EC data affected by air masses coming from the nearby shore.  
490 Due to the controlled nature of the River Kitinen, it does not necessarily represent a river in a natural state. Nonetheless, as most of the world's rivers are dammed, the response of fluxes and the dissolved  $\text{CO}_2$  partial pressure on the discharge could provide valuable insight into gas emissions from controlled rivers.

*Data availability.* Data are available at <https://doi.org/10.5281/zenodo.14257924>.

*Author contributions.* TV, ALi, ALo, SM and IM designed the field experiments. AV, SG, ALi, ALo and SM carried out the field measure-  
495 ments. ALi measured the  $p_{\text{CO}_2}$  in air and water. AV and IM conducted the eddy covariance data processing and analysis. AV, TV and IM prepared the manuscript with contribution from all coauthors.

*Competing interests.* The authors declare no competing interests.

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## References

- Åberg, J., Jansson, M., and Jonsson, A.: Importance of water temperature and thermal stratification dynamics for temporal variation of surface water CO<sub>2</sub> in a boreal lake, *J. Geophys. Res.*, 115, G02 024, <https://doi.org/10.1029/2009JG001085>, 2010.
- 505 Alin, S. R., de Fátima F.L. Rasesa, M., Salimon, C. I., Richey, J. E., Holtgrieve, G. W., Krusche, A. V., and Snidvongs, A.: Physical controls on carbon dioxide transfer velocity and flux in low-gradient river systems and implications for regional carbon budgets, *J. Geophys. Res.*, 116, G01 009, <https://doi.org/10.1029/2010JG001398>, 2011.
- Attermeyer, K., Casas-Ruiz, J. P., Fuss, T., Pastor, A., Cauvy-Fraunié, S., Sheath, D., Nydahl, A. C., Doretto, A., Portela, A. P., Doyle, B. C., Simov, N., Gutmann Roberts, C., Niedrist, G. H., Timoner, X., Evtimova, V., Barral-Fraga, L., Bašić, T., Audet, J., Deininger, A., 510 Busst, G., Fenoglio, S., Catalán, N., de Eyto, E., Pilotto, F., Mor, J.-R., Monteiro, J., Fletcher, D., Noss, C., Colls, M., Nagler, M., Liu, L., González-Quijano, C. R., Romero, F., Pansch, N., Ledesma, J. L. J., Pegg, J., Klaus, M., Freixa, A., Herrero Ortega, S., Mendoza-Lera, C., Bednařík, A., Fonvielle, J. A., Gilbert, P. J., Kenderov, L. A., Rulík, M., and Bodmer, P.: Carbon dioxide fluxes increase from day to night across European streams, *Commun. Earth Environ.*, 2, 1–8, <https://doi.org/10.1038/s43247-021-00192-w>, 2021.
- Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, 515 R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, *Adv. Ecol. Res.*, 30, 113–175, 2000.
- Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Aalto, R. E., and Yoo, K.: Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere, *Front. Ecol. Environ.*, 9, 53–60, <https://doi.org/10.1890/100014>, 2011.
- Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and 520 future, *Glob. Change Biol.*, 9, 479–492, 2003.
- Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M.: Technical Note: Cost-efficient approaches to measure carbon dioxide (CO<sub>2</sub>) fluxes and concentrations in terrestrial and aquatic environments using mini loggers, *Biogeosciences*, 12, 3849–3859, <https://doi.org/10.5194/bg-12-3849-2015>, 2015.
- Blomquist, B. W., Fairall, C. W., Huebert, B. J., and Wilson, S. T.: Direct measurement of the oceanic carbon monoxide flux by eddy 525 correlation, *Atmos. Meas. Tech.*, 5, 3069–3075, <https://doi.org/10.5194/amt-5-3069-2012>, 2012.
- Burba, G., Schmidt, A., Scott, R. L., Nakai, T., Kathilankal, J., Fratini, G., Hanson, C., Law, B., McDermitt, D. K., Eckles, R., Furtaw, M., and Velgersdyk, M.: Calculating CO<sub>2</sub> and H<sub>2</sub>O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio, *Glob. Change Biol.*, 18, 385–399, <https://doi.org/10.1111/j.1365-2486.2011.02536.x>, 2012.
- Campeau, A. and del Giorgio, P. A.: Patterns in CH<sub>4</sub> and CO<sub>2</sub> concentrations across boreal rivers: Major drivers and implications for fluvial 530 greenhouse emissions under climate change scenarios, *Glob. Change Biol.*, 20, 1075–1088, <https://doi.org/10.1111/gcb.12479>, 2014.
- Campeau, A., Lapierre, J.-F., Vachon, D., and del Giorgio, P. A.: Regional contribution of CO<sub>2</sub> and CH<sub>4</sub> fluxes from the fluvial network in a lowland boreal landscape of Québec, *Global Biogeochemical Cy.*, 28, 57–69, <https://doi.org/10.1002/2013GB004685>, 2014.
- Chen, H., Winderlich, J., Gerbig, C., Hofer, A., Rella, C. W., Crosson, E. R., Van Pelt, A. D., Steinbach, J., Kolle, O., Beck, V., Daube, B. C., Gottlieb, E. W., Chow, V. Y., Santoni, G. W., and Wofsy, S. C.: High-accuracy continuous airborne measurements of greenhouse 535 gases (CO<sub>2</sub> and CH<sub>4</sub>) using the cavity ring-down spectroscopy (CRDS) technique, *Atmos. Meas. Tech.*, 3, 375–386, 2010.
- Chien, H., Zhong, Y.-Z., Yang, K.-H., and Cheng, Hao, Y.: Diurnal variability of CO<sub>2</sub> flux at coastal zone of Taiwan based of eddy covariance observations, *Cont. Shelf Res.*, 162, 27–38, <https://doi.org/10.1016/j.csr.2018.04.006>, 2018.

- Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Mid-  
delburg, J. J., and Melack, J.: Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget, *Ecosystems*,  
540 10, 171–184, <https://doi.org/10.1007/s10021-006-9013-8>, 2007.
- Crawford, J. T., Striegl, R. G., Wickland, K. P., Dornblaser, M. M., and Stanley, E. H.: Emissions of carbon dioxide and methane from a  
headwater stream network of interior Alaska, *J. Geophys. Res.-Biogeo.*, 118, 482–494, <https://doi.org/10.1002/jgrg.20034>, 2013.
- Czikowsky, M. J., MacIntyre, S., Tedford, E. W., Vidal, J., and Miller, S. D.: Effects of wind and buoyancy on carbon dioxide distribution  
and air-water flux of a stratified temperate lake, *J. Geophys. Res.-Biogeo.*, 123, 2305–2322, <https://doi.org/10.1029/2017JG004209>, 2018.
- 545 Denfeld, B. A., Frey, K. E., Sobczak, W. V., Mann, P. J., and Holmes, R. M.: Summer CO<sub>2</sub> evasion from streams and rivers in the Kolyma  
River basin, north-east Siberia, *Polar Res.*, 32, 19704, <https://doi.org/10.3402/polar.v32i0.19704>, 2013.
- Drake, T. W., Raymond, P. A., and Spencer, R. G. M.: Terrestrial carbon inputs to inland waters: A current synthesis of estimates and  
uncertainty, *Limnol. Oceanogr. Letters*, 3, 132–142, <https://doi.org/10.1002/lol2.10055>, 2018.
- Erkkilä, K.-M., Ojala, A., Bastviken, D., Biermann, T., Heiskanen, J. J., Lindroth, A., Peltola, O., Rantakari, M., Vesala, T., and Mammarella,  
550 I.: Methane and carbon dioxide fluxes over a lake: comparison between eddy covariance, floating chambers and boundary layer method,  
*Biogeosciences*, 15, 429–445, <https://doi.org/10.5194/bg-15-429-2018>, 2018.
- Eugster, W., DelSontro, T., Shaver, G. R., and Kling, G. W.: Interannual, summer, and diel variability of CH<sub>4</sub> and CO<sub>2</sub> effluxes from Toolik  
Lake, Alaska, during the ice-free periods 2010–2015, *Environ. Sci.-Proc. Imp.*, 22, 2181–2198, <https://doi.org/10.1039/D0EM00125B>,  
2020.
- 555 Foken, T. and Wichura, B.: Tools for quality assessment of surface-based flux measurements, *Agr. Forest Meteorol.*, 78, 83–105, 1996.
- Golub, M., Koupaei-Abyazani, N., Vesala, T., Mammarella, I., Ojala, A., Bohrer, G., Weyhenmeyer, G. A., Blanken, P. D., Eugster, W.,  
Koebisch, F., Chen, J., Czajkowski, K., Deshmukh, C., Guerin, F., Heiskanen, J., Humphreys, E., Jonsson, A., Karlsson, J., Kling, G., Lee,  
X., Liu, H., Lohila, A., Lundin, E., Morin, T., Podgrajsek, E., Provenzale, M., Rutgersson, A., Sachs, T., Sahlee, E., Serca, D., Shao, C.,  
Spence, C., Strachan, I. B., Xiao, W., and Desai, A. R.: Diel, seasonal, and inter-annual variation in carbon dioxide effluxes from lakes  
560 and reservoirs, *Environ. Res. Lett.*, 18, <https://doi.org/10.1088/1748-9326/acfb97>, 2023.
- Gómez-Gener, L., Rocher-Ros, G., Battin, T., Cohen, M. J., Dalmagro, H. J., Dinsmore, K. J., Drake, T. W., Duvert, C., Enrich-Prast, A.,  
Horgby, Å., Johnson, M. S., Kirk, L., Machado-Silva, F., Marzolf, N. S., McDowell, M. J., McDowell, W. H., Miettinen, H., Ojala,  
A. K., Peter, H., Pumpanen, J., Ran, L., Riveros-Iregui, D. A., Santos, I. R., Six, J., Stanley, E. H., Wallin, M. B., White, S. A.,  
and Sponseller, R. A.: Global carbon dioxide efflux from rivers enhanced by high nocturnal emissions, *Nat. Geosci.*, 14, 289–294,  
565 <https://doi.org/10.1038/s41561-021-00722-3>, 2021.
- Günthel, M., Klawonn, I., Woodhouse, J., Bižić, M., Ionescu, D., Ganzert, L., Kümmel, S., Nijenhuis, I., Zoccarato, L., Grossart, H.-P.,  
and Tang, K. W.: Photosynthesis-driven methane production in oxic lake water as an important contributor to methane emission, *Limnol.*  
*Oceanogr.*, 65, 2853–2865, <https://doi.org/10.1002/lno.11557>, 2020.
- Guseva, S., Aurela, M., Cortés, A., Kivi, R., Lotsari, E., MacIntyre, S., Mammarella, I., Ojala, A., Stepanenko, V., Uotila, P., Vähä, A.,  
570 Vesala, T., Wallin, M. B., and Lorke, A.: Variable physical drivers of near-surface turbulence in a regulated river, *Water Resour. Res.*, 57,  
[e2020WR027939](https://doi.org/10.1029/2020WR027939), <https://doi.org/10.1029/2020WR027939>, 2021.
- Hall, R. O. and Ulseth, A. J.: Gas exchange in streams and rivers, *WIREs Water*, 7, e1391, <https://doi.org/10.1002/wat2.1391>, 2019.
- Hall, R. O., Tank, J. L., Baker, M. A., Rosi-Marshall, E. J., and Hotchkiss, E. R.: Metabolism, gas exchange, and carbon spiraling in rivers,  
*Ecosystems*, 19, 73–86, <https://doi.org/10.1007/s10021-015-9918-1>, 2016.

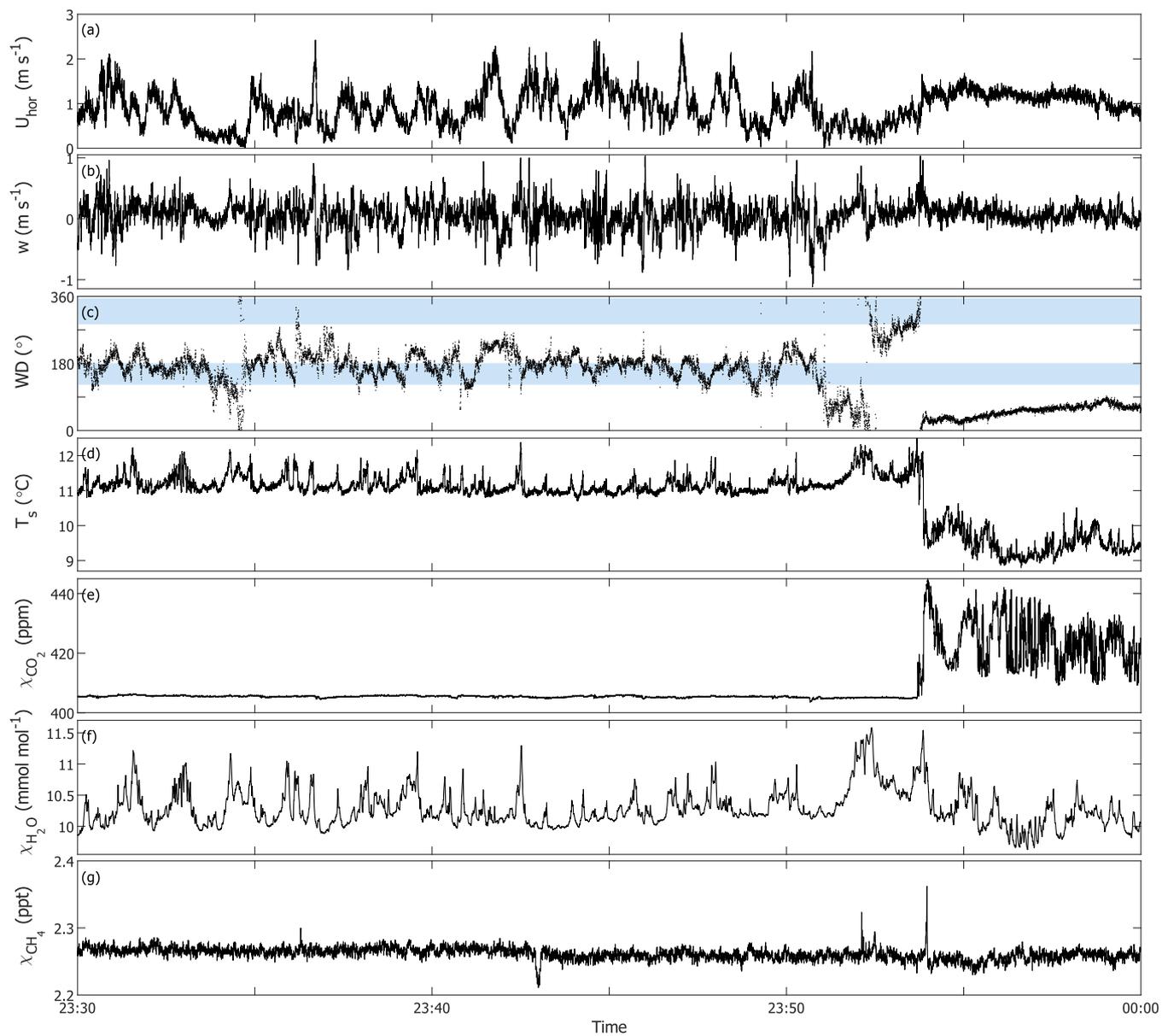
- 575 Hotchkiss, E., Hall Jr, R., Sponseller, R., Butman, D., Klaminder, J., Laudon, H., Rosvall, M., and Karlsson, J.: Sources of and processes controlling CO<sub>2</sub> emissions change with the size of streams and rivers, *Nat. Geosci.*, 8, 696–699, <https://doi.org/10.1038/ngeo2507>, 2015.
- Huotari, J., Haapanala, S., Pumpanen, J., Vesala, T., and Ojala, A.: Efficient gas exchange between a boreal river and the atmosphere, *Geophys. Res. Lett.*, 40, 5683–5686, <https://doi.org/10.1002/2013GL057705>, 2013.
- Hutchins, R. H. S., Prairie, Y. T., and del Giorgio, P. A.: Large-scale landscape drivers of CO<sub>2</sub>, CH<sub>4</sub>, DOC, and DIC in boreal river networks, *Global Biogeochemical Cy.*, 33, 125–142, <https://doi.org/10.1029/2018GB006106>, 2019.
- 580 Hutchins, R. H. S., Casas-Ruiz, J. P., Prairie, Y. T., and del Giorgio, P. A.: Magnitude and drivers of integrated fluvial network greenhouse gas emissions across the boreal landscape in Québec, *Water Res.*, 173, 115–156, <https://doi.org/10.1016/j.watres.2020.115556>, 2020.
- Huttunen, J., Väisänen, T., Hellsten, S., Heikkinen, M., Nykänen, H., Jungner, H., Niskanen, A., Virtanen, M., Lindqvist, O., Nenonen, O., and Martikainen, P.: Fluxes of CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O in hydroelectric reservoirs Lokka and Porttipahta in the northern boreal zone in Finland, *Global Biogeochemical Cy.*, 16, 1003, <https://doi.org/10.1029/2000GB001316>, 2002.
- 585 Kljun, N., Calanca, P., Rotach, M. W., and Schmid, H. P.: A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP), *Geosci. Model Dev.*, 8, 3695–3713, <https://doi.org/10.5194/gmd-8-3695-2015>, 2015.
- Kohonen, K.-M., Kolari, P., Kooijmans, L. M. J., Chen, H., Seibt, U., Sun, W., , and Mammarella, I.: Towards standardized processing of eddy covariance flux measurements of carbonyl sulfide, *Atmos. Meas. Tech.*, 13, 3957–3975, <https://doi.org/10.5194/amt-13-3957-2020>,
- 590 2020.
- Kristensen, L., Mann, J., Oncley, S. P., and Wyngaard, J. C.: How close is close enough when measuring scalar fluxes with displaced sensors?, *J. Atmos. Ocean. Tech.*, 14, 814–821, 1997.
- Lauerwald, R., Laruelle, G. G., Hartmann, J., Ciais, P., and Regnier, P. A. G.: Spatial patterns in CO<sub>2</sub> evasion from the global river network, *Global Biogeochemical Cy.*, 29, 534–554, <https://doi.org/10.1002/2014GB004941>, 2015.
- 595 Li, M., Peng, C., Zhang, K., Xu, L., Wang, J., Yang, Y., Li, P., Liu, Z., and He, N.: Headwater stream ecosystem: an important source of greenhouse gases to the atmosphere, *Water Res.*, 190, 116–138, <https://doi.org/10.1016/j.watres.2020.116738>, 2021.
- Liu, H., Peters, G., and Foken, T.: New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer, *Bound.-Lay. Meteorol.*, 100, 459–468, 2001.
- Liu, S. and Raymond, P. A.: Hydrologic controls on pCO<sub>2</sub> and CO<sub>2</sub> efflux in US streams and rivers, *Limnol. Oceanogr. Letters*, 3, 428–435, <https://doi.org/10.1002/lol2.10095>, 2018.
- 600 Liu, S., Lu, X. X., Xia, X., Yang, X., and Ran, L.: Hydrological and geomorphological control on CO<sub>2</sub> outgassing from low-gradient large rivers: An example of the Yangtze River system, *J. Hydrol.*, 550, 26–41, <https://doi.org/10.1016/j.jhydrol.2017.04.044>, 2017.
- Lorke, A., Bodmer, P., Noss, C., Alshboul, Z., Koschorreck, M., Somlai-Haase, C., Bastviken, D., Flury, S., McGinnis, D. F., Maeck, A., Müller, D., and Premke, K.: Technical note: drifting versus anchored flux chambers for measuring greenhouse gas emissions from running waters, *Biogeosciences*, 12, 7013–7024, <https://doi.org/10.5194/bg-12-7013-2015>, 2015.
- 605 Lynch, J. K., Beatty, C. M., Seidel, M. P., Jungst, L. J., and DeGrandpre, M. D.: Controls of riverine CO<sub>2</sub> over an annual cycle determined using direct, high temporal resolution pCO<sub>2</sub> measurements, *J. Geophys. Res.*, 115, G03016, <https://doi.org/10.1029/2009JG001132>, 2010.
- Mammarella, I., Launiainen, S., Gronholm, T., Keronen, P., Pumpanen, J., Rannik, Ü., and Vesala, T.: Relative humidity effect on the high-frequency attenuation of water vapor flux measured by a closed-path eddy covariance system, *J. Atmos. Ocean. Tech.*, 26, 1856–1866, <https://doi.org/10.1175/2009JTECHA1179.1>, 2009.

- Mammarella, I., Nordbo, A., Rannik, Ü., Haapanala, S., Levula, J., Laakso, H., Ojala, A., Peltola, O., Heiskanen, J., Pumpanen, J., and Vesala, T.: Carbon dioxide and energy fluxes over a small boreal lake in Southern Finland, *J. Geophys. Res.-Biogeo.*, 120, 1296–1314, <https://doi.org/10.1002/2014JG002873>, 2015.
- 615 Mammarella, I., Peltola, O., Nordbo, A., Järvi, L., and Rannik, Ü.: Quantifying the uncertainty of eddy covariance fluxes due to the use of different software packages and combinations of processing steps in two contrasting ecosystems, *Atmos. Meas. Tech.*, 9, 4915–4933, <https://doi.org/10.5194/amt-9-4915-2016>, 2016.
- Nemitz, E., Mammarella, I., Ibrom, A., Aurela, M., Burba, G., Dengel, S., Gielen, B., Grelle, A., Heinesch, B., Herbst, M., Hörtnagl, L., Klemmedtsson, L., Lindroth, A., Lohila, A., McDermitt, D., Meier, P., Merbold, L., Nelson, D., Nicolini, G., Nilsson, M., Peltola, O., Rinne, 620 J., and Zahniser, M.: Standardization of eddy covariance flux measurements of methane and nitrous oxide, *Int. Agrophys.*, 32, 517–549, <https://doi.org/10.1515/intag-2017-0042>, 2018.
- Oswald, K., Milucka, J., Brand, A., Littmann, S., Wehrli, B., Kuypers, M. M. M., and Schubert, C. J.: Light-dependent aerobic methane oxidation reduces methane emissions from seasonally stratified lakes, *PLoS ONE*, 10, e0132574, <https://doi.org/10.1371/journal.pone.0132574>, 2015.
- 625 Rannik, Ü. and Vesala, T.: Autoregressive filtering versus linear detrending in estimation of fluxes by the eddy covariance method, *Bound.-Lay. Meteorol.*, 91, 259–280, 1999.
- Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P., and Guth, P.: Global carbon dioxide emissions from inland waters, *Nature*, 503, 355–359, <https://doi.org/10.1038/nature12760>, 2013.
- 630 Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luysaert, S., Andersson, A. J., Arndt, S., Arnosti, C., Borges, A. V., Dale, A. W., Gallego-Sala, A., Godderis, Y., Goossens, N., Hartmann, J., Heinze, C., Ilyina, T., Joos, F., LaRowe, D. E., Leifeld, J., Meysman, F. J. R., Munhoven, G., Raymond, P. A., Spahni, R., Suntharalingam, P., and Thullner, M.: Anthropogenic perturbation of the carbon fluxes from land to ocean, *Nat. Geosci.*, 6, 597–607, <https://doi.org/10.1038/ngeo1830>, 2013.
- Rocher-Ros, G., Sponseller, R. A., Lidberg, W., Mörth, C.-M., and Giesler, R.: Landscape process domains drive patterns of CO<sub>2</sub> evasion 635 from river networks, *Limnol. Oceanogr. Letters*, 4, 87–95, <https://doi.org/10.1002/lol2.10108>, 2019.
- Rocher-Ros, G., Sponseller, R. A., Bergström, A., Myrstener, M., and Giesler, R.: Stream metabolism controls diel patterns and evasion of CO<sub>2</sub> in Arctic streams, *Glob. Change Biol.*, 26, 1400–1413, <https://doi.org/10.1111/gcb.14895>, 2020.
- Rocher-Ros, G., Stanley, E. H., Loken, L. C., Casson, N. J., Raymond, P. A., Liu, S., Amatulli, G., and Sponseller, R. A.: Global methane emissions from rivers and streams, *Nature*, 621, 530–535, <https://doi.org/10.1038/s41586-023-06344-6>, 2023.
- 640 Rovelli, L., Olde, L. A., Heppell, C. M., Binley, A., Yvon-Durocher, G., Glud, R. N., and Trimmer, M.: Contrasting biophysical controls on carbon dioxide and methane outgassing from streams, *J. Geophys. Res.-Biogeo.*, 127, e2021JG006328, <https://doi.org/10.1029/2021JG006328>, 2021.
- Sabbatini, S., Mammarella, I., Arriga, N., Fratini, G., A., G., Hörtnagl, L., Ibrom, A., Longdoz, B., Mauder, M., Merbold, L., Metzger, S., Montagnani, L., Pitacco, A., Rebmann, C., Sedlak, P., Sigut, L., Vitale, D., and Papale, D.: Eddy covariance raw data processing for CO<sub>2</sub> 645 and energy flux calculation at ICOS ecosystem stations, *Int. Agrophys.*, 32, 495–515, <https://doi.org/10.1515/intag-2017-0043>, 2018.
- Scofield, V., Melack, J. M., Barbosa, P. M., Amaral, J. H. F., Forsberg, B. R., and Farjalla, V. F.: Carbon dioxide outgassing from Amazonian aquatic ecosystems in the Negro River basin, *Biogeochemistry*, 129, 77–91, <https://doi.org/10.1007/s10533-016-0220-x>, 2016.

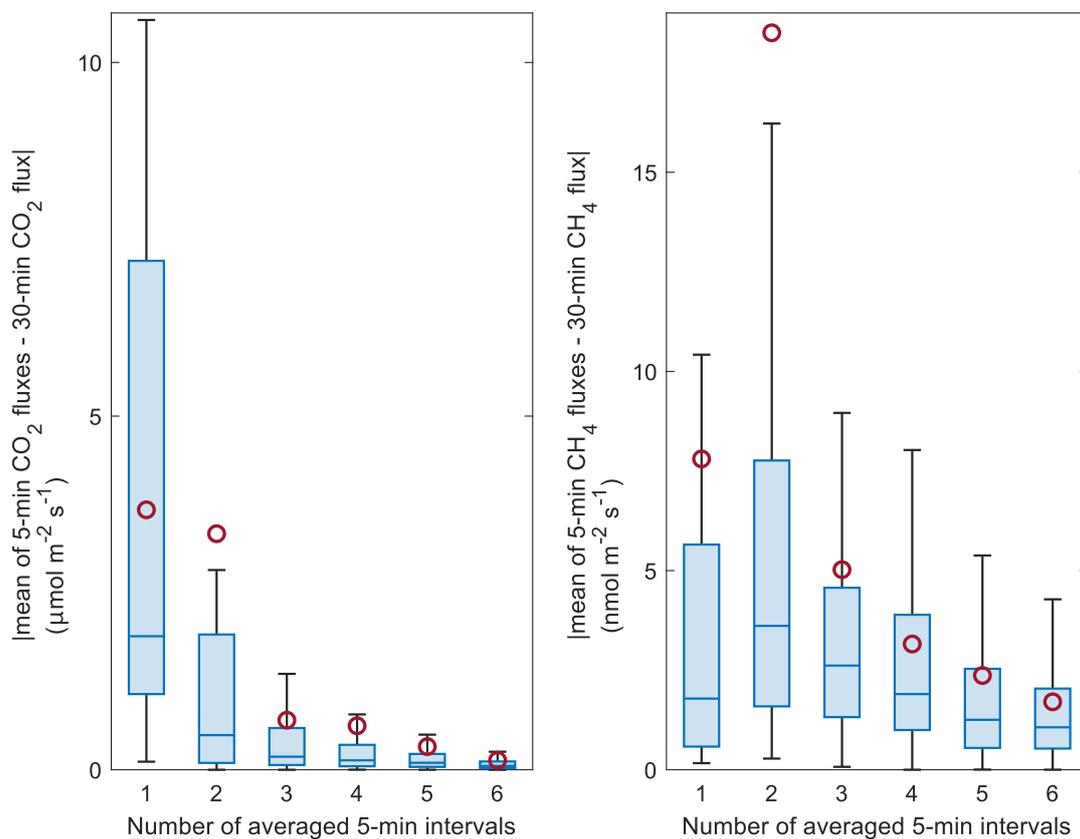
- Serikova, S., Pokrovsky, O. S., Ala-aho, P., Kazantsev, V., Kirpotin, S. N., Kopysov, S. G., Krickov, I. V., Laudon, H., Manasypov, R. M., Shirokova, L. S., Soulsby, C., Tetzlaff, D., and Karlsson, J.: High riverine CO<sub>2</sub> emissions at the permafrost boundary of Western Siberia, *Nat. Geosci.*, 11, 825–829, <https://doi.org/10.1038/s41561-018-0218-1>, 2018.
- Sieczko, A. K., Duc, N. T., Schenk, J., Pajala, G., Rudberg, D., Sawakuchi, H. O., and Bastviken, D.: Diel variability of methane emissions from lakes, *P. Natl. Acad. Sci. USA*, 117, 21 488–21 494, <https://doi.org/10.1073/pnas.2006024117>, 2020.
- Silvennoinen, H., Liikanen, A., Rintala, J., and Martikainen, P. J.: Greenhouse gas fluxes from the eutrophic Temmesjoki River and its Estuary in the Liminganlahti Bay (the Baltic Sea), *Biogeochemistry*, 90, 193–208, <https://doi.org/10.1007/s10533-008-9244-1>, 2008.
- Spank, U., Hehn, M., Keller, P., Koschorreck, M., and Bernhofer, C.: A Season of Eddy-covariance Fluxes Above an Extensive Water Body Based on Observations from a Floating Platform, *Bound.-Lay. Meteorol.*, 174, 433–464, <https://doi.org/10.1007/s10546-019-00490-z>, 2020.
- Stanley, E. H., Casson, N. J., Christel, S. T., Crawford, J. T., Loken, L. C., and Oliver, S. K.: The ecology of methane in streams and rivers: patterns, controls, and global significance, *Ecol. Monogr.*, 86, 146–171, <https://doi.org/10.1890/15-1027>, 2016.
- Stepanenko, V., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., and Vesala, T.: LAKE 2.0: a model for temperature, methane, carbon dioxide and oxygen dynamics in lakes, *Geosci. Model Dev.*, 9, 1977–2006, <https://doi.org/10.5194/gmd-9-1977-2016>, 2016.
- Striegl, R. G., Dornblaser, M. M., McDonald, C. P., Rover, J. R., and Stets, E. G.: Carbon dioxide and methane emissions from the Yukon River system, *Global Biogeochemical Cy.*, 26, GB0E05, <https://doi.org/10.1029/2012GB004306>, 2012.
- Verpoorter, C., Kutser, T., Seekell, D. A., and Tranvik, L. J.: A global inventory of lakes basen on high-resolution satellite imagery, *Geophys. Res. Lett.*, 41, 6396–6402, <https://doi.org/10.1002/2014GL060641>, 2014.
- Vickers, D. and Mahrt, L.: Quality control and flux sampling problems for tower and aircraft data, *J. Atmos. Ocean. Tech.*, 14, 512–526, 1997.
- Yvon-Durocher, G., Allen, A. P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., Thanh-Duc, N., and Del Giorgio, P. A.: Methane fluxes show consistent temperature dependence across microbial to ecosystem scales, *Nature*, 507, 488–491, <https://doi.org/10.1038/nature13164>, 2014.

## Appendix A: Data screening based on the wind direction

Figure A1 shows an example of a case when the calculated wind direction was within the accepted sectors but most of the instantaneous wind was not. In this case, the bulk wind direction was 155°. However, only during the intervals 23:30–23:35 and 23:45–23:50 the 5-minute bulk wind direction fell within the accepted sectors. The horizontal wind speed varied between 0 and 3 m s<sup>-1</sup> and the vertical wind between -1 and 1 m s<sup>-1</sup>. A sudden change in the wind direction occurred at 23:54 when the wind abruptly turned east, i.e. from the forest. This caused a sudden 2°C drop in the measured sonic temperature and an increase of approximately 30 ppm in the CO<sub>2</sub> mixing ratio. The effect on H<sub>2</sub>O and CH<sub>4</sub> was not as pronounced. The 30-minute CO<sub>2</sub> flux was as high as 11 μmol m<sup>-2</sup> s<sup>-1</sup>, caused mainly by the sudden increase in the mixing ratio, but with the 5-minute wind direction screening, the flux was only 0.09 μmol m<sup>-2</sup> s<sup>-1</sup>.



**Figure A1.** Example of a case with deviating wind direction on 7 August 2018 between 23:30 and 00:00 UTC. All data were measured at 10 Hz. (a) Horizontal wind speed. (b) Vertical wind speed. (c) Wind direction. The light-blue bars mark the accepted wind sectors. (d) Sonic temperature. (e) CO<sub>2</sub> dry mixing ratio. (f) H<sub>2</sub>O mixing ratio. (g) CH<sub>4</sub> dry mixing ratio.



**Figure A2.** Absolute difference between the averaged 5 minutes and 30 minutes fluxes for CO<sub>2</sub> (a) and CH<sub>4</sub> (b) as a function of the number of averaged 5-minute intervals. The boxes indicate the upper and lower quartiles and the median. The whiskers are the maximum and minimum of nonoutliers. The circles indicate means. Outliers are not shown.