Supporting Information for

Eddy covariance data reveal that a small freshwater reservoir emits a substantial amount of carbon dioxide and methane

Alexandria G. Hounshell[1, †], Brenda M. D'Acunha[2], Adrienne Breef-Pilz[1], Mark S. Johnson[2,3], R. Quinn Thomas[1,4], Cayelan C. Carey[1]

[1] Department of Biological Sciences, Virginia Tech, Blacksburg, VA, USA, [2] Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada, [3] Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC, Canada, [4] Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA, USA

Corresponding author: Alexandria G. Hounshell (alexgh@vt.edu)

† Current affiliation: National Centers for Coastal Ocean Science, National Oceanographic and Atmospheric Administration, Beaufort, NC, 28516, alexandria.hounshell@noaa.gov

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Introduction

The supplementary information additional figures (Figures S1-S13) and tables (Tables S1-S11) used as supporting information in the associated manuscript.

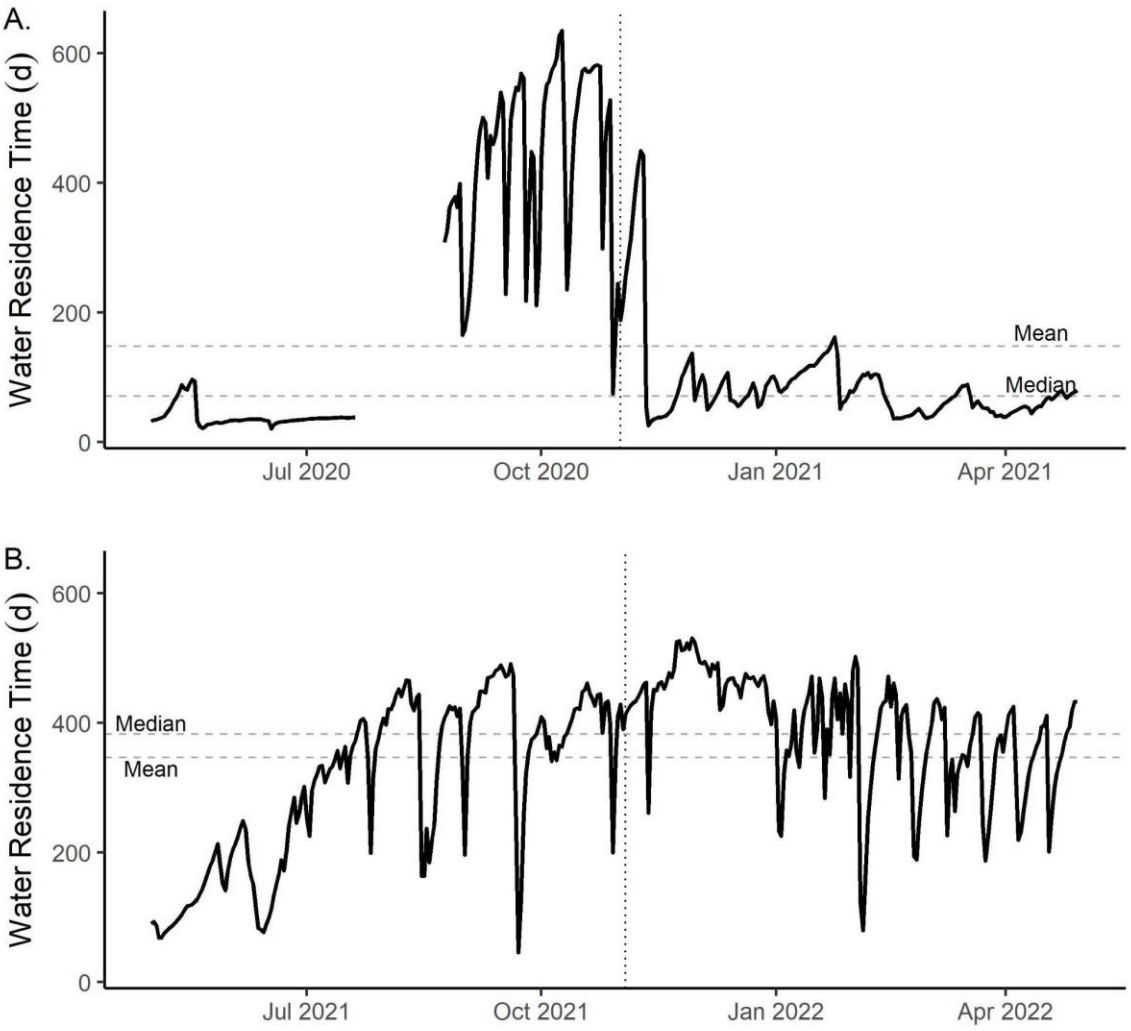

Fig. S1. Water residence time (days, d) plotted for A. Year 1 (May 2020-April 2021) and B. Year 2 (May 2021-April 2022). The vertical dashed line represents fall turnover for each year. The horizontal dashed lines correspond to the mean and median, respectively (Year 1: mean = 148 d, median = 71 d; Year 2: mean = 347 d, median = 383 d).

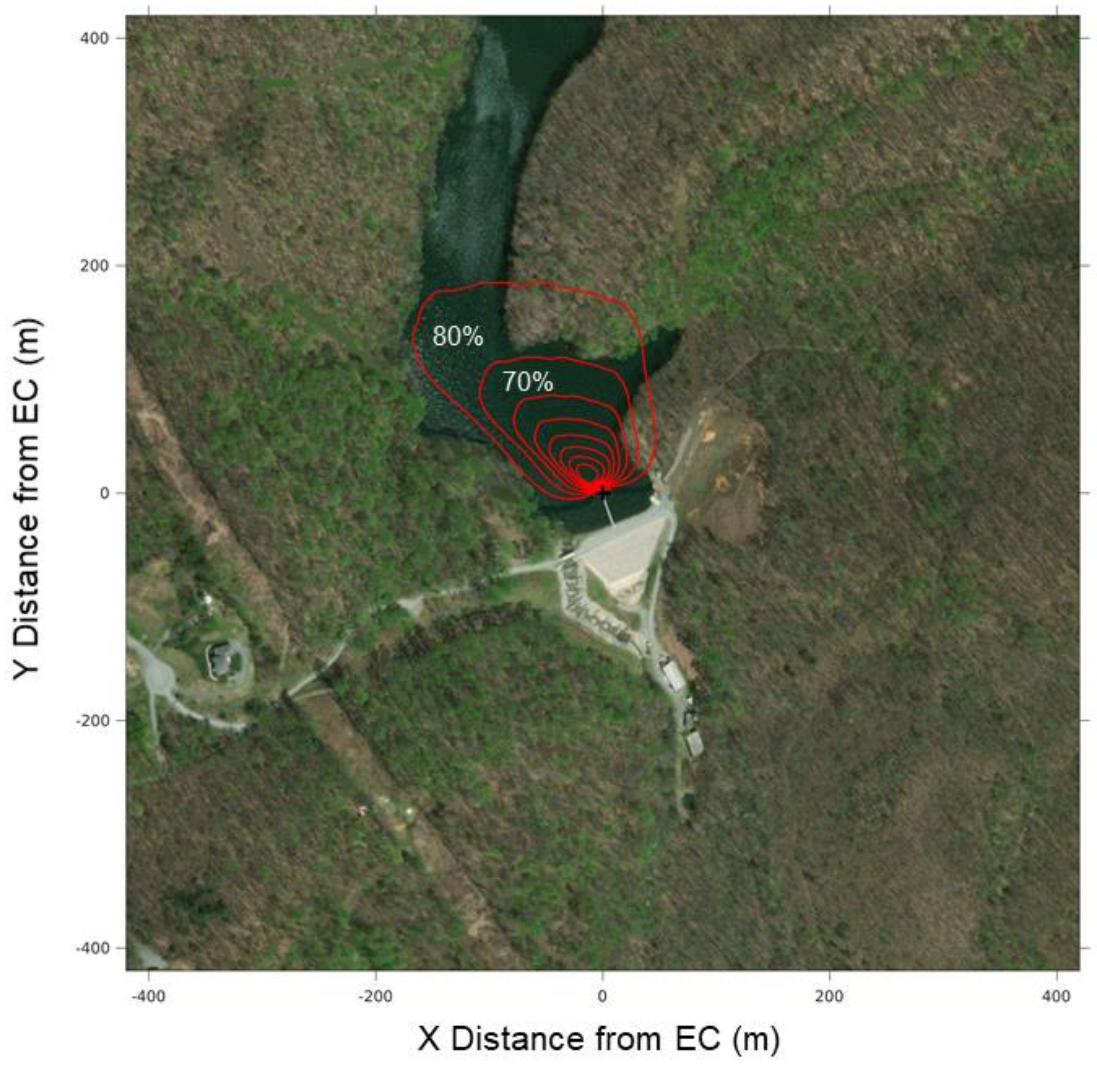

Figure S2. Cumulative footprint for fluxes retained for analysis during the two years of eddy covariance (EC) fluxes measured from Falling Creek Reservoir following methods in Kljun et al. (2015). The 10-80% isolines are plotted as red circles around the EC system (denoted as the black plus-sign). Additional data filtering was conducted to remove fluxes within the 80% isoline which originated over land.

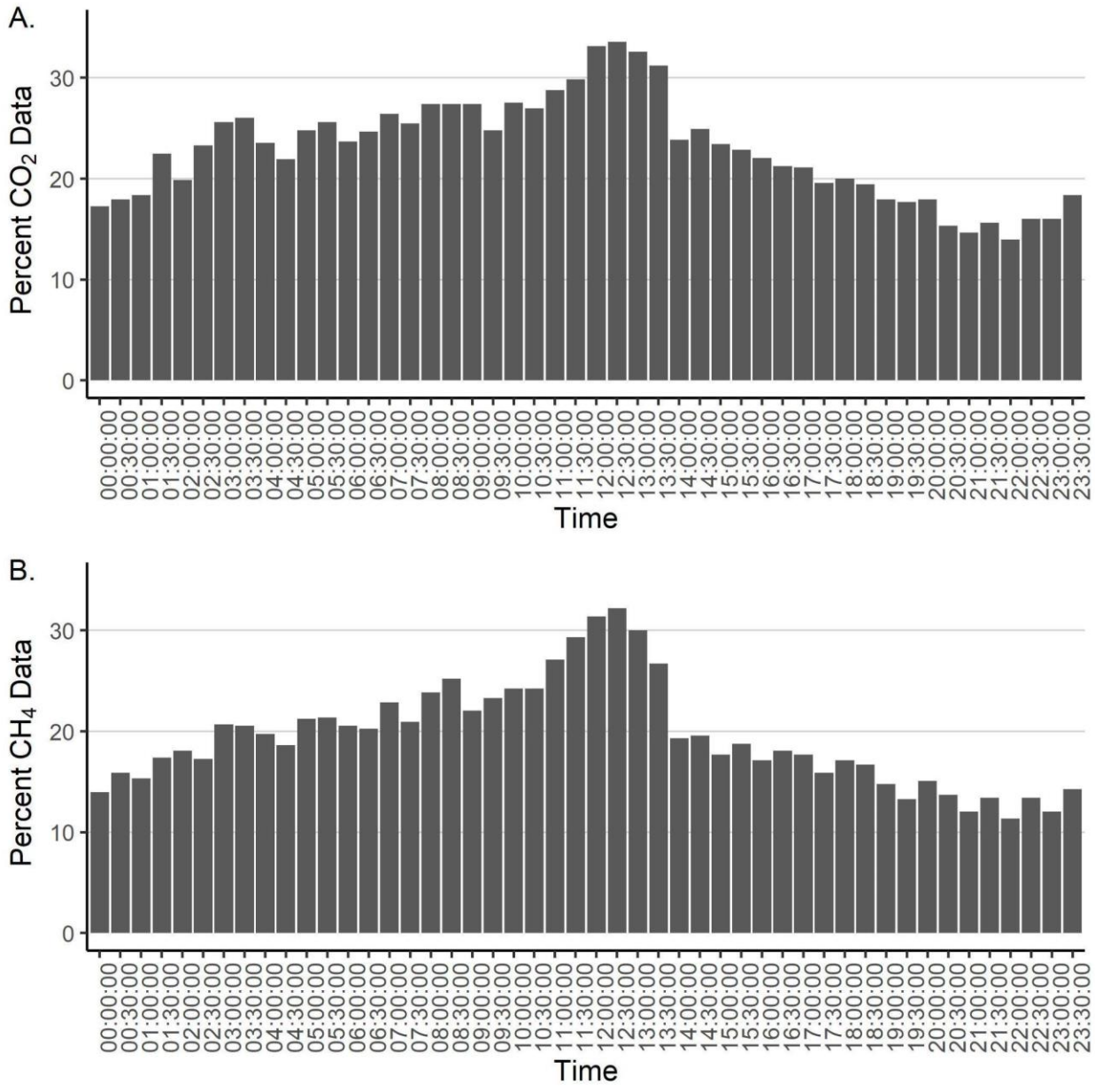

Figure S3. Barplot of average percent of data availability for A. carbon dioxide (CO_2) and B. methane (CH_4) fluxes distributed throughout the day (half-hourly from 0:00 to 23:30).

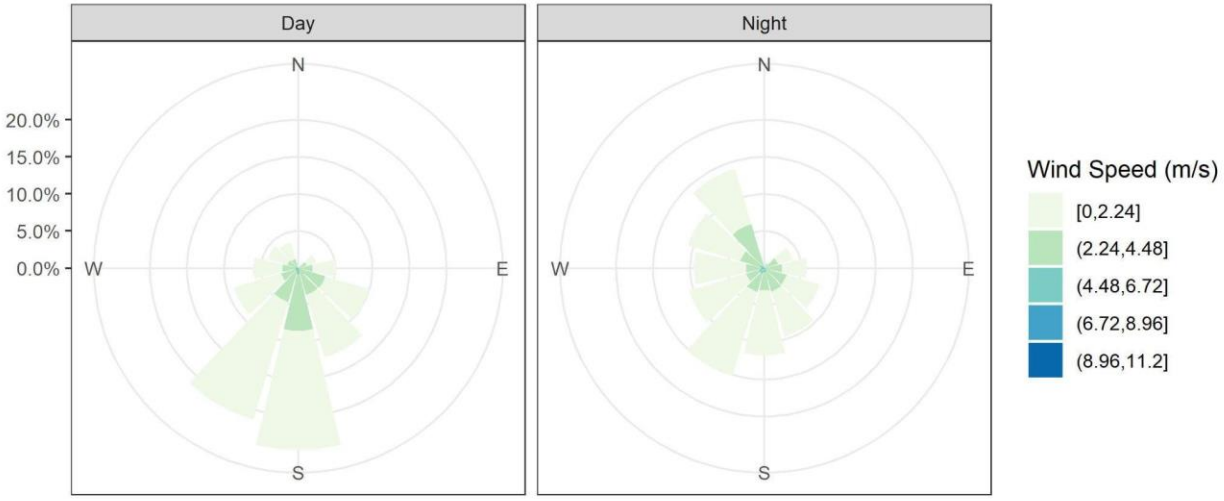

Figure S4. Windrose of all measured windspeed and direction during the study period separated by A. Day (shortwave radiation in > 0 W m^2) and B. Night (shortwave radiation in < 0 W m^2) collected from the meteorological stations deployed at the dam.

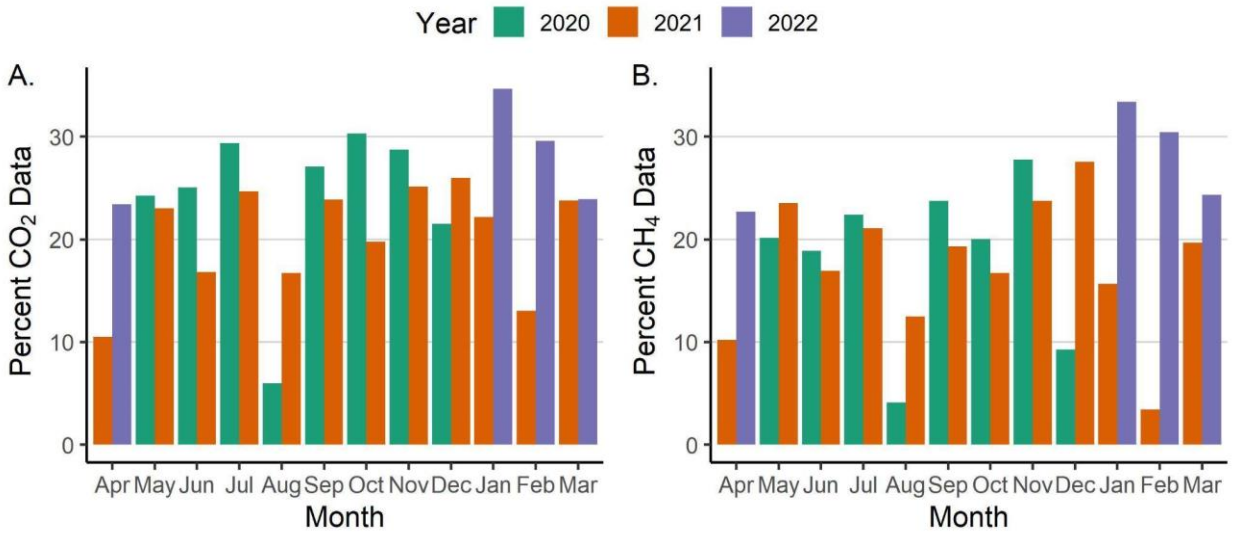

Figure S5. Barplot of average percent of data availability for A. carbon dioxide (CO_2) and B. methane (CH_4) fluxes distributed throughout each month and year of the study period.

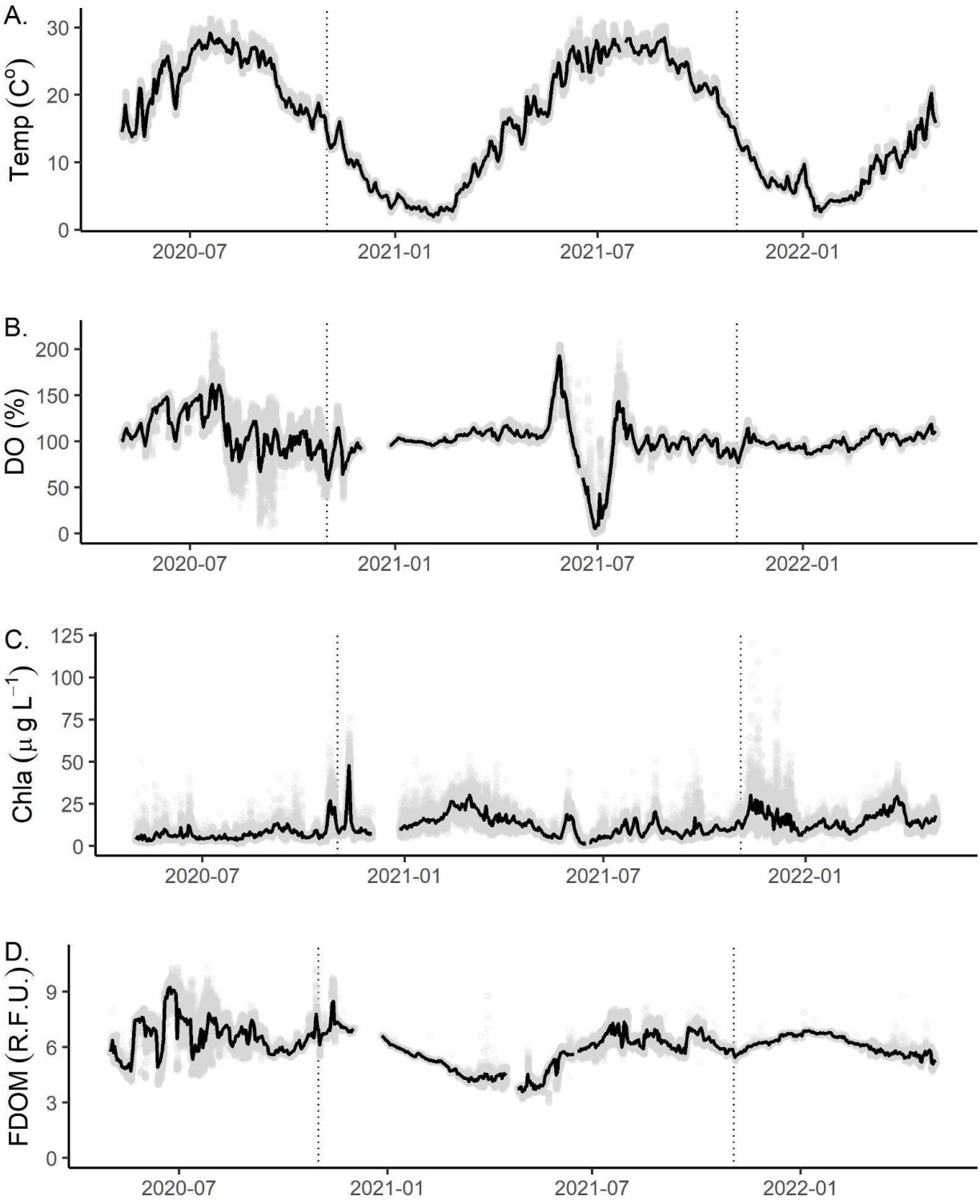

Figure S6. Environmental variables measured during the study period, including A. Surface Water Temperature (Temp, °C) measured at 0.1 m below the surface; B. Dissolved oxygen (DO, percent saturation, %) measured at 1.6 m; C. Chlorophyll-*a* (Chl-a, µg L^{-1})

measured at 1.6 m; and D. fluorescent dissolved organic matter (fDOM, Relative Fluorescence Units, RFU) measured at 1.6 m. Solid black lines represent the daily mean while the light grey points represent individual measurements made every 15 minutes for inflow and every 10 minutes for all other variables. The dashed vertical black line indicates reservoir fall turnover for both years.

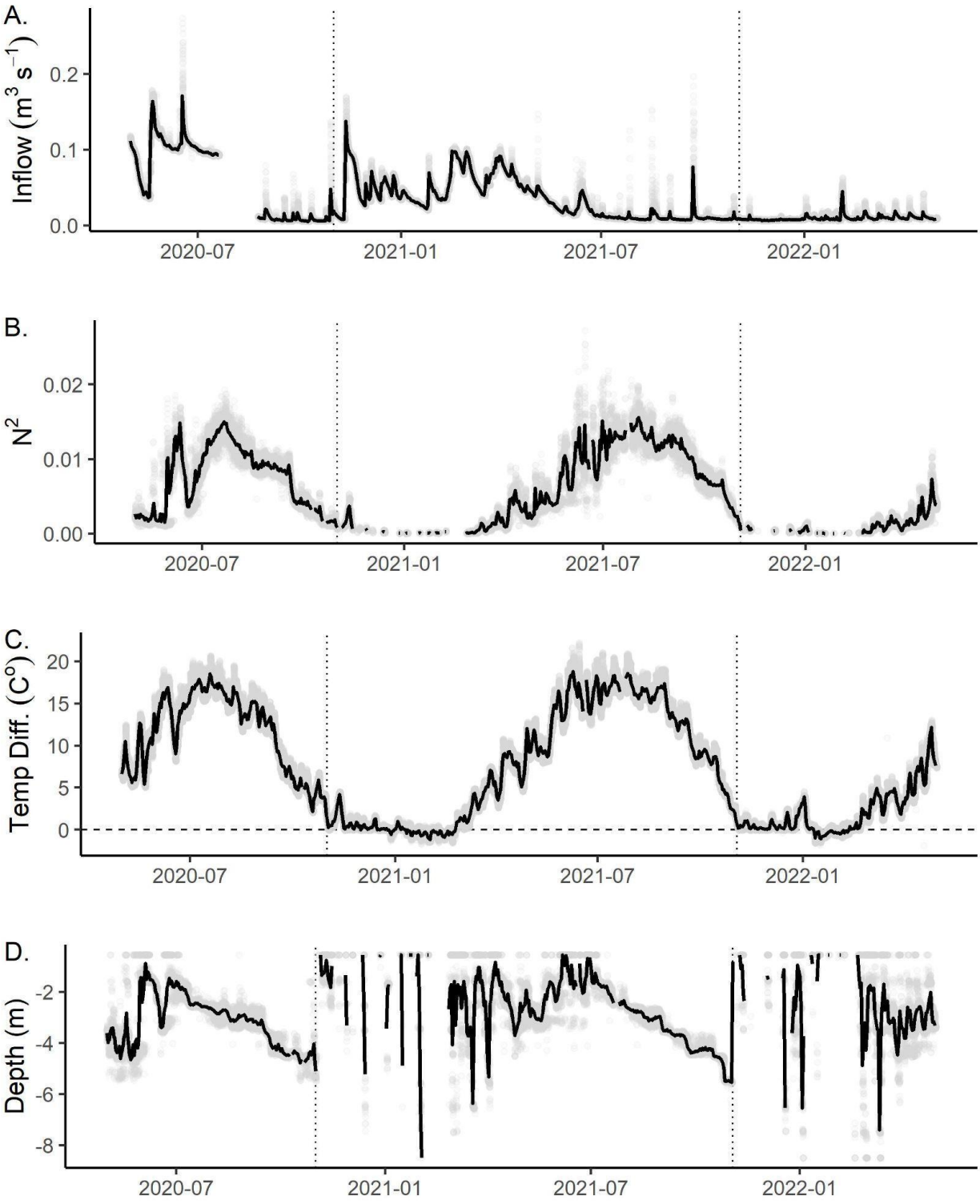

Figure S7. Environmental variables measured during the study period, including A. Inflow (m^3 s^{-1}) measured at the primary inflow to Falling Creek Reservoir; B. Buoyancy frequency (N^2) calculated from thermal profiles at the deepest point in the reservoir; C.

The temperature difference (Temp Diff., °C) measured from the surface (0.1 m) and bottom (9 m) at the deepest point of the reservoir; and D. Thermocline depth (Depth, m) calculated from thermal profiles deployed at the deepest point of the reservoir. Solid black lines represent the daily mean while the light grey points represent individual measurements made every 15 minutes for inflow and every 10 minutes for all other variables. The dashed vertical black line indicates reservoir fall turnover for each year.

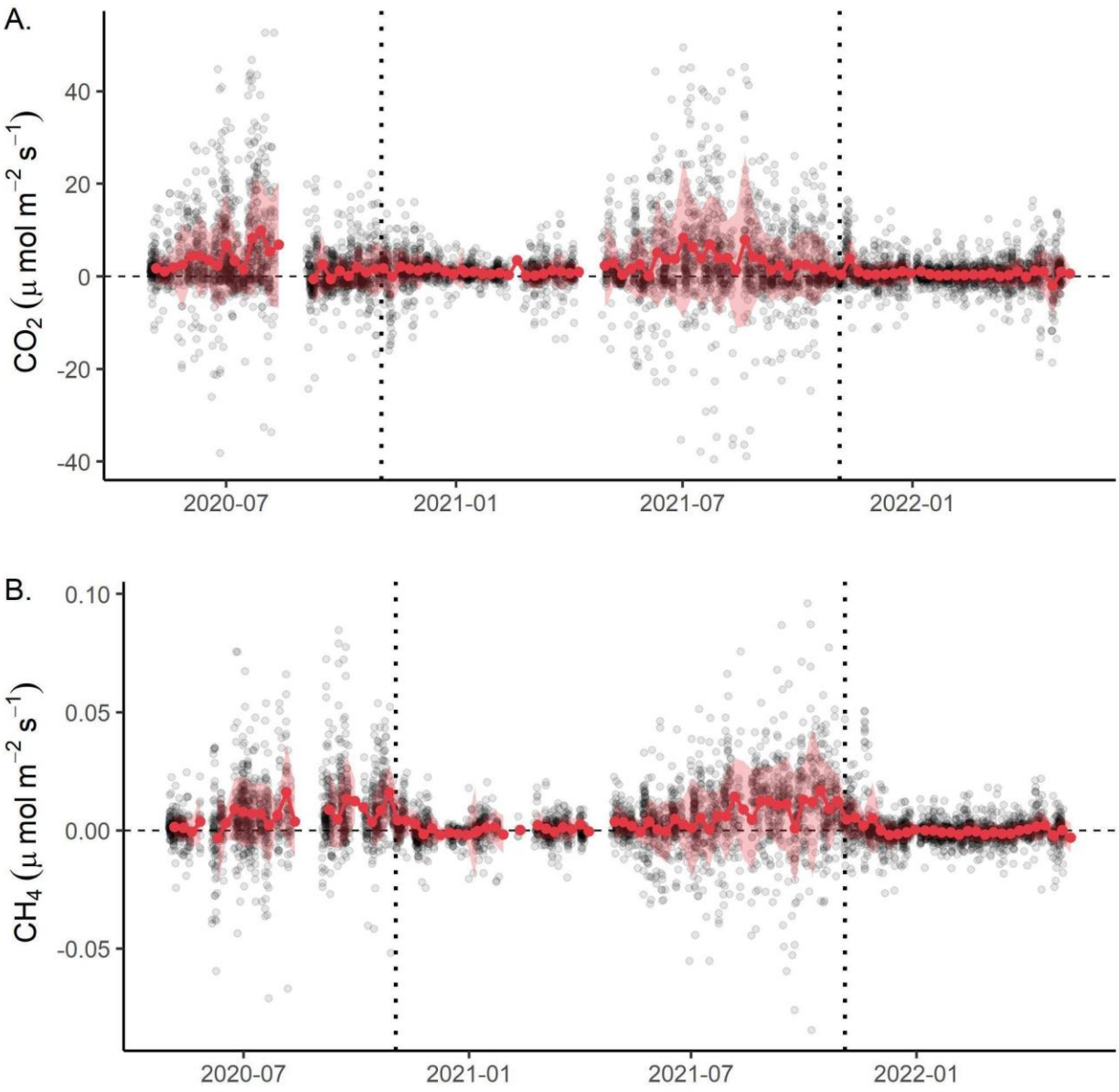

Figure S8. A. Mean weekly carbon dioxide fluxes (CO_2, μmol m^{-2} s^{-1}) and B. mean weekly methane fluxes (CH_4, μmol m^{-2} s^{-1}) aggregated from measured eddy covariance data from 1 May 2020 to 30 April 2021 in Falling Creek Reservoir plotted as a red line with dots. The red shaded area corresponds to the standard deviation (±1 S.D.) of aggregated fluxes for both measured and gap-filled values. Black dots represent measured half-hourly fluxes. The vertical dashed line corresponds to reservoir fall turnover for each year.

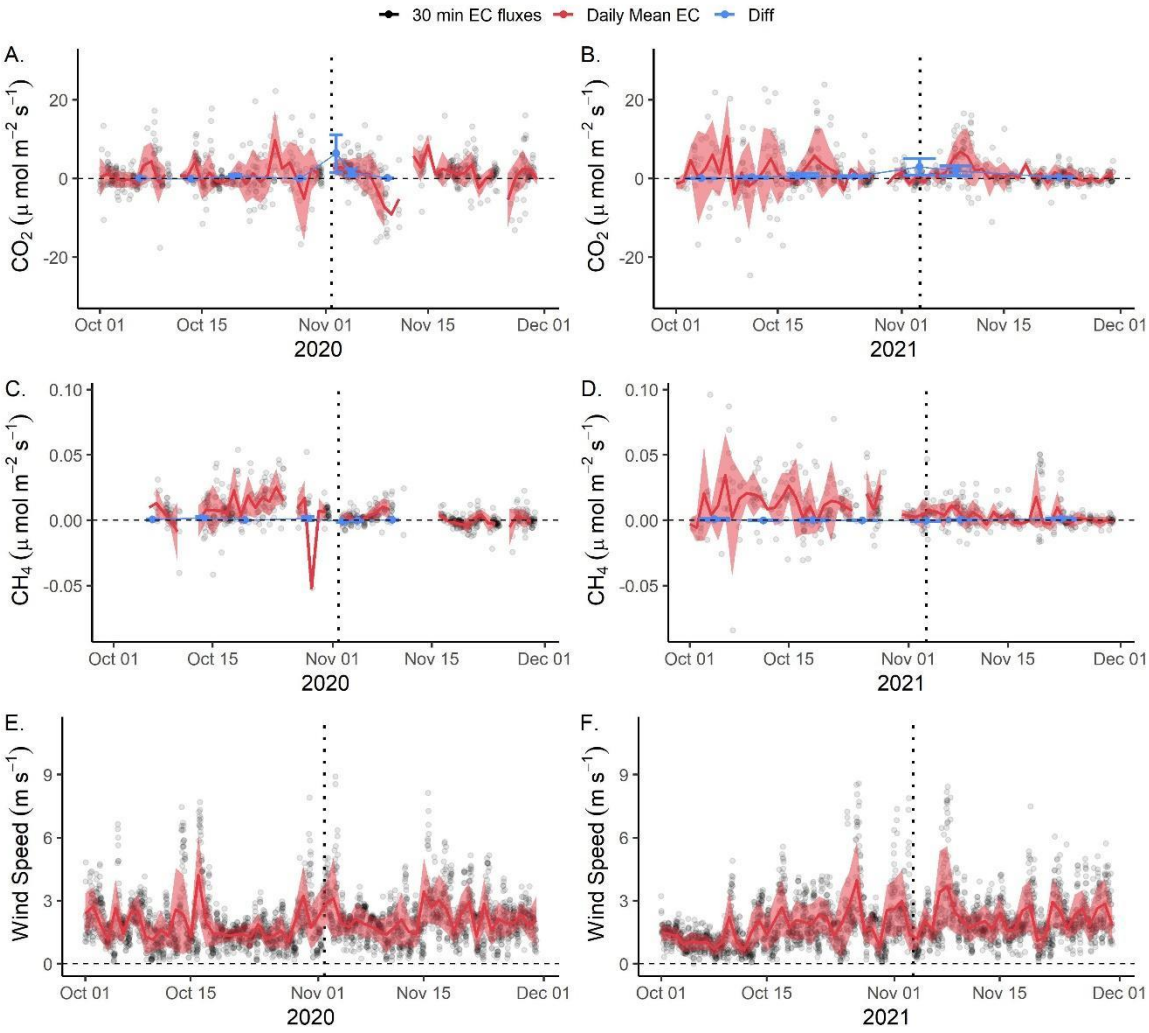

Figure S9. Mean daily A., B. Carbon dioxide (CO_2, μmol m^{-2} s^{-1}) and C., D. Mean daily methane fluxes (CH_4 μmol m^{-2} s^{-1}) for 2020 and 2021, respectively, around reservoir fall turnover (01 November 2021 and 03 November 2022, respectively). Mean daily wind is also plotted for E. 2020 and F. 2021. Grey dots represent measured half-hourly fluxes from the EC system (CO_2, CH_4) and the meteorological station deployed at the dam of Falling Creek Reservoir (Wind speed). The dark red line represents daily mean fluxes or wind speed. The shaded red area represents ±1 standard deviation of the daily 30-minute fluxes or wind speed. The vertical dotted line indicates reservoir fall turnover.

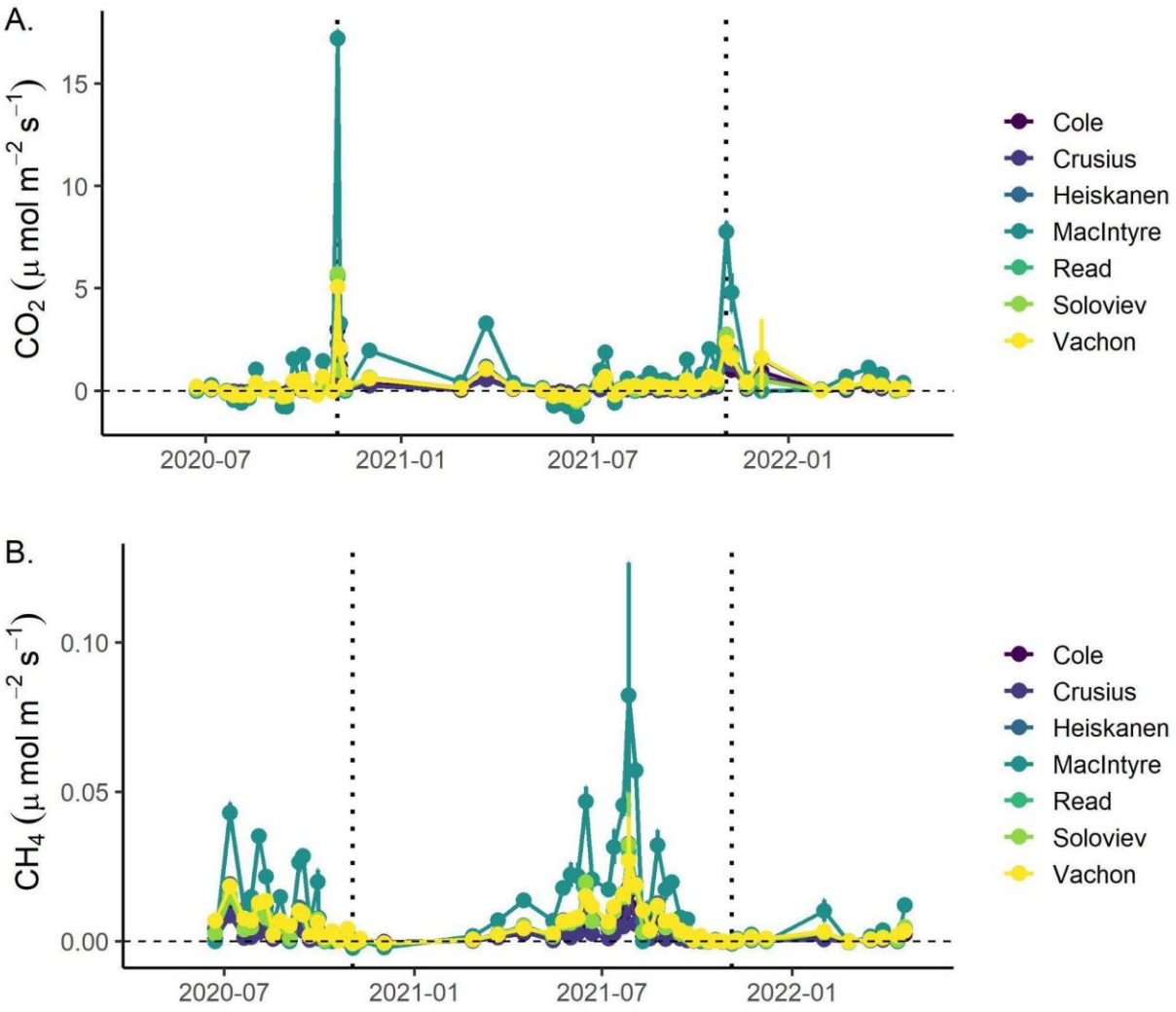

Figure S10. Discrete diffusive fluxes calculated for A. carbon dioxide (CO_2, µmol m^{-2} s^{-1}) and B. methane (CH_4, µmol m^{-2} s^{-1}) during the study period (1 May 2020 to 30 April 2022) using multiple gas transfer coefficient models (k; Winslow et al. 2016; Cole and Caraco, 1998; Crusius and Wannikof, 2003; Vachon and Prairie, 2013; MacIntyre et al. 2010; Heiskanen et al. 2014; Read et al. 2012; Soloviev et al. 2007). Points represent the mean of two replicates calculated for each k method and the error bars are the standard deviation (±1 S.D.). The dashed horizontal line indicates zero fluxes and the dotted vertical line corresponds to reservoir fall turnover on 1 November 2020 and 3 November 2021, respectively.

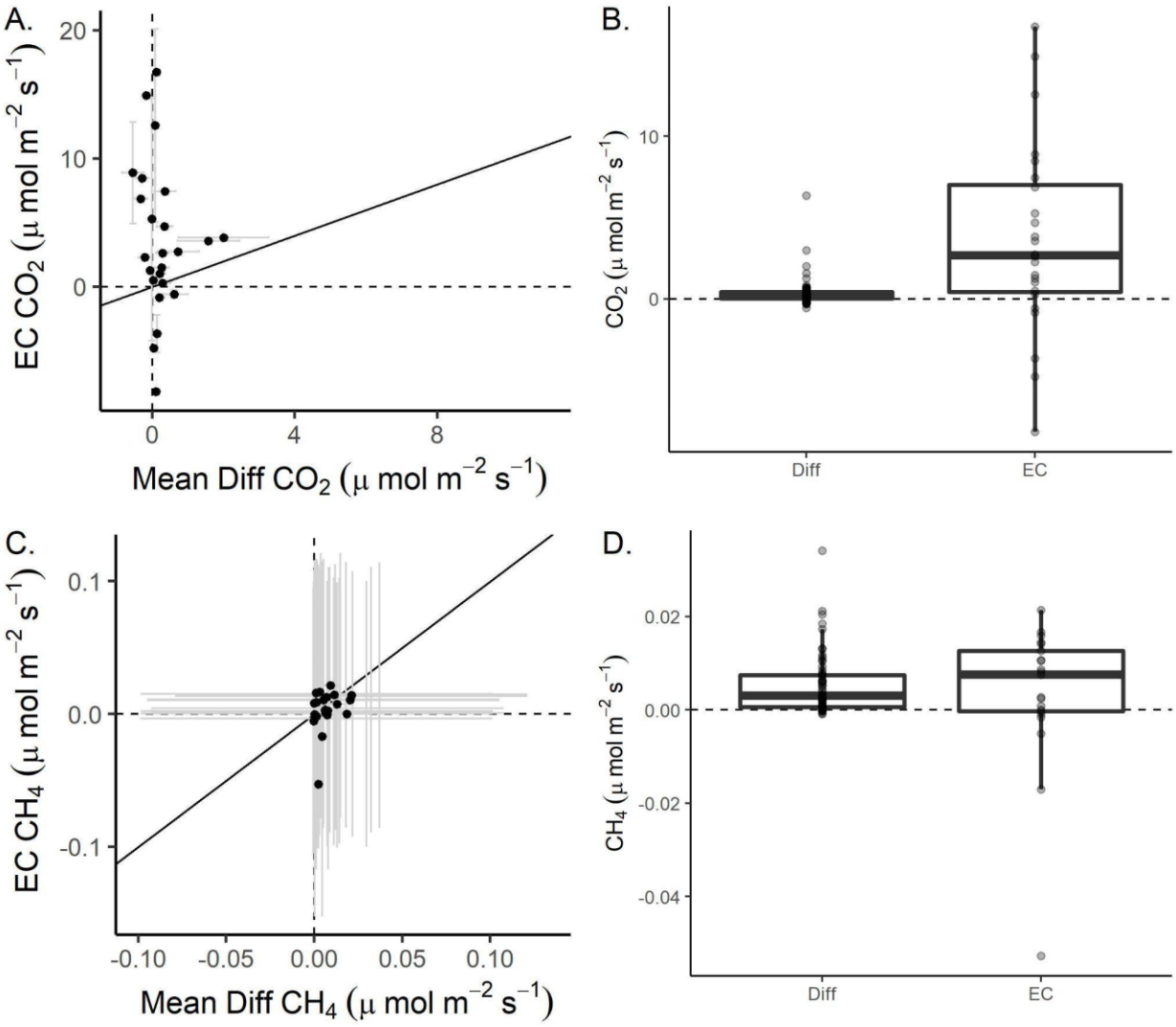

Figure S11. Instantaneous mean diffusive fluxes compared to mean hourly fluxes obtained using the eddy covariance (EC) system for A. carbon dioxide (CO_2, μmol m^{-2} s^{-1}; n = 24 observations) and C. methane (CH_4, μmol m^{-2} s^{-1}; n = 21 observations). Standard deviation is plotted as grey bars for both mean diffusive fluxes estimated for two replicates using all k methods (see main manuscript text) and for mean hourly fluxes obtained using the EC. Results are also compared as boxplots for B. CO_2 and D. CH_4 where the mean instantaneous fluxes are plotted as the grey points; the box represents the 25th and 75th percentiles; the median is represented as the bolded line; and the whiskers represent the minimum and maximum values (1.5x interquartile range). Dashed vertical and horizontal lines correspond to zero fluxes; the one-to-one line is plotted as a solid black line.

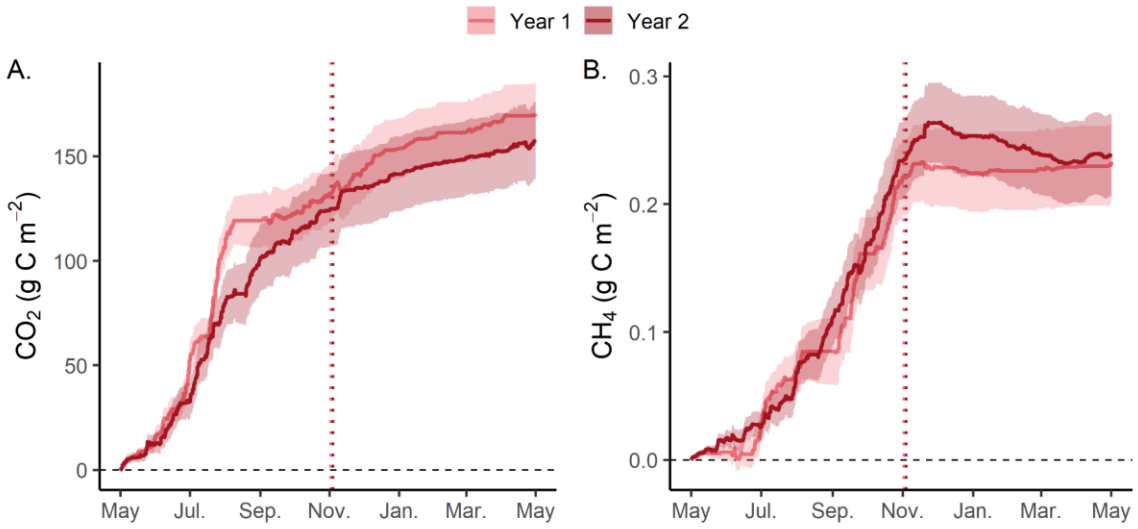

Figure S12. Annual cumulative fluxes for A. carbon dioxide (CO_2, g C m^{-2}) and B. methane (CH_4, g C m^{-2}) using measured eddy covariance fluxes from Falling Creek Reservoir for Year 1 (May 2020-April 2021; pink) and Year 2 (May 2021-April 2022; dark red). Shaded areas correspond to the aggregated standard deviation (±1 S.D.) of measurements. The horizontal dashed line corresponds to zero and the vertical dotted line indicates reservoir fall turnover for both years. Note: these cumulative fluxes only represent 22 and 24% of CO_2 fluxes and 16 and 23% of CH_4 fluxes measured directly using the EC system in year 1 and year 2, respectively. When upscaling to the full year, this would lead to 774 and 657 g CO_2 m^{-2} for year 1 and year 2 and 1.45 and 1.03 g CH_4 m^{-2}, respectively.

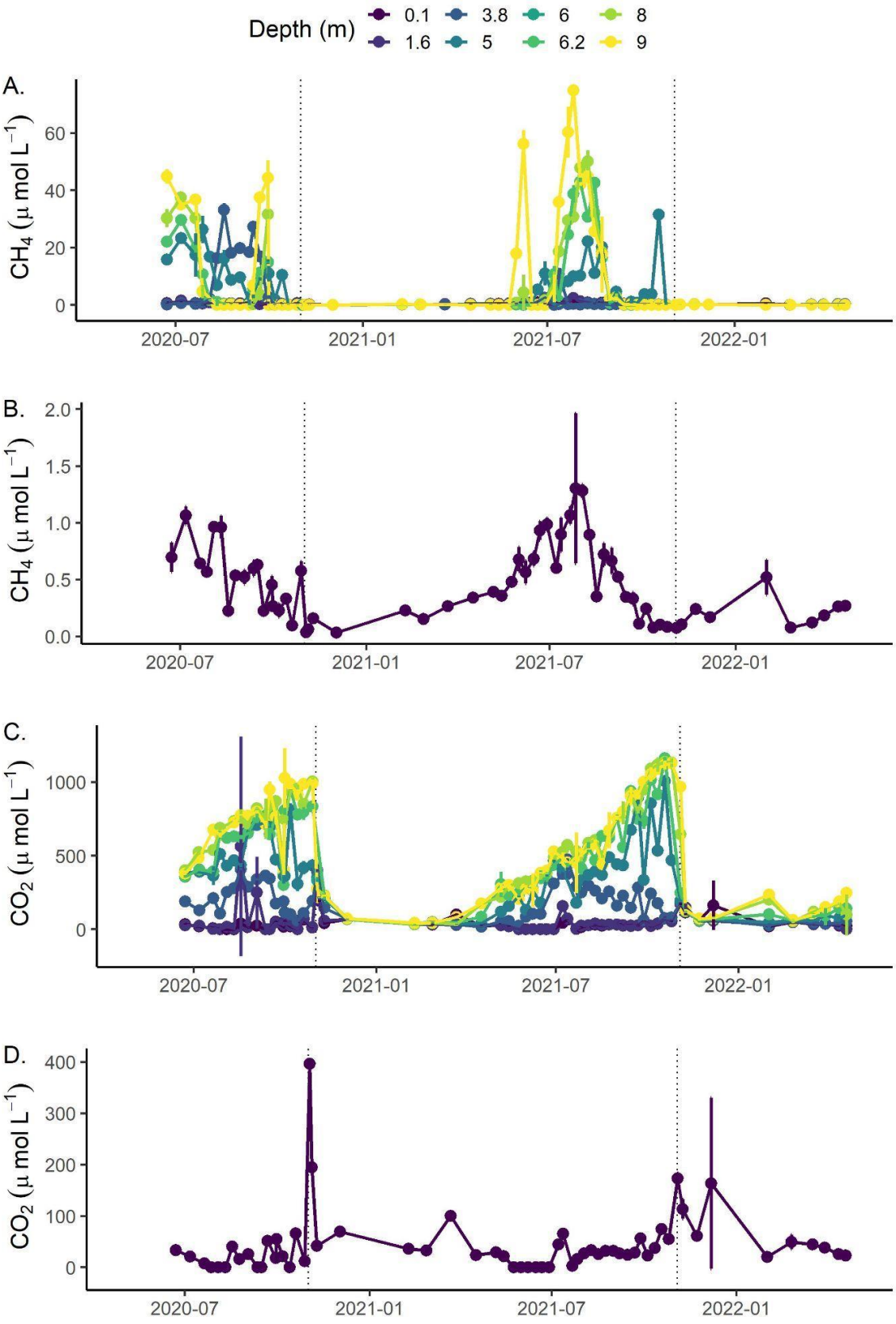
Depth (m)
0.1
1.6
3.8
5
6
6.2
8
9
A.
CH_4 (μ mol L^{-1})
0
20
40
60
2020-07
2021-01
2021-07
2022-01
B.
CH_4 (μ mol L^{-1})
0.0
0.5
1.0
1.5
2.0
2020-07
2021-01
2021-07
2022-01
C.
CO_2 (μ mol L^{-1})
0
500
1000
2020-07
2021-01
2021-07
2022-01
D.
CO_2 (μ mol L^{-1})
0
100
200
300
400
2020-07
2021-01
2021-07
2022-01

Fig. S13. A. Water column dissolved methane (CH_4, μmol m^{-2} s^{-1}) plotted for multiple depths throughout the water column; B. Dissolved CH_4 measured at the surface of the reservoir (0.1 m); C. Dissolved carbon dioxide (CO_2, μmol m^{-2} s^{-1}) measured at multiple depths; and D. dissolved CO_2 measured at 0.1 m. All samples were collected at the deepest point of the reservoir located near the eddy covariance system (EC). The mean and standard deviation of two replicate samples are reported. The dashed, vertical line corresponds to fall turnover for Year 1 and Year 2.

	Percent available CO_2 fluxes (%)	**Percent available CH_4 fluxes (%)**
Raw data available	84	73
Removing fluxes from behind the dam (<80° and >250°)	59	52
QA/QC* of fluxes, LE**, and H***	39	33
Removing fluxes outside of reservoir footprint	29	25
Removing fluxes with low u*	23	19

* QA/QC = Quality assurance/quality control
** Latent energy flux
*** Sensible heat flux

Table S1. Percent of measured carbon dioxide (CO_2) and methane (CH_4) fluxes retained for analysis following data post-processing and various steps of data post-processing. See main manuscript for description of each post-processing step; all code is available in (Carey et al. 2022a).

	Start Date	**End Date**
Intermittent Ice on	10 January 2021	10 February 2021
Intermittent Ice on	11 January 2022	14 January 2022
Continuous Ice on	16 January 2022	10 February 2022

Table S2. Start and end dates used to define intermittent ice-on and continuous ice-on periods during the winter for 2020-2021 and winter 2021-2022 in Falling Creek Reservoir (Carey and Breef-Pilz, 2022).

Parameter	% Missing	R^2	r	Linear equation
Wind speed	12	0.60	0.78	EC = Met*0.50 + 0.19
Air Temperature	39	0.97	0.98	EC = Met*0.95 - 1.01
Sonic Air Temperature	39	0.97	0.98	EC = Met*1.03 - 0.56
Relative Humidity	41	0.75	0.87	EC = Met*0.80 + 13.76

Table S3. Meteorological variables derived from the eddy covariance (EC) system which were estimated with meteorological data obtained from the meteorological (Met) station deployed on the dam of Falling Creek Reservoir. The percent of missing data (% Missing) represents the percent of data missing from the EC system over the two-year monitoring period that was estimated from the meteorological data. The R^2 is included for the linear relationship between the EC and Met data along with the linear equation used for estimation, r denotes Spearman rho correlation. Parameters include: wind speed (m s^{-1}), air temperature (K), sonic air temperature (K), and relative humidity (%).

	Daily						
	DO % Sat.	**Chl-a ($\mu g\ L^{-1}$)**	**fDOM (RFU)**	**Inflow ($m^3\ s^{-1}$)**	**Temp Diff.**	**N^2**	**Thermo Depth (m)**
Surface Temp. (ºC)	0.04	-0.54	0.30	0.02	0.94	0.91	-0.01
DO % Sat.		0.10	0.01	0.39	0.12	0.00	-0.05
Chl-a ($\mu g\ L^{-1}$)			-0.18	-0.16	-0.53	-0.49	-0.02
fDOM (RFU)				0.13	0.23	0.28	-0.05
Inflow ($m^3\ s^{-1}$)					0.14	-0.03	-0.18
Temp Diff.						0.92	-0.17
N^2							-0.15
	Weekly						
Surface Temp. (ºC)	0.10	-0.52	0.18	0.06	0.95	0.93	0.16
DO % Sat.		0.07	-0.07	0.39	0.17	0.06	-0.01
Chl-a ($\mu g\ L^{-1}$)			-0.25	-0.19	-0.52	-0.50	-0.07
fDOM (RFU)				0.11	0.11	0.21	-0.09
Inflow ($m^3\ s^{-1}$)					0.14	0.00	-0.17
Temp Diff.						0.95	0.01
N^2							-0.01
	Monthly						
Surface Temp. (ºC)	0.16	-0.68	0.23	0.03	0.96	0.95	0.03
DO % Sat.		-0.15	-0.14	0.65	0.23	0.11	0.00
Chl-a ($\mu g\ L^{-1}$)			-0.45	-0.18	-0.68	-0.64	0.05
fDOM (RFU)				-0.03	0.16	0.30	-0.04
Inflow ($m^3\ s^{-1}$)					0.13	0.01	-0.27

Temp Diff.						0.96	-0.12
N^2							-0.11

Table S4. Correlations (Pearson's rho) among environmental parameters identified for the ARIMA analyses, including surface temperature (surface temp., °C), percent dissolved oxygen saturation (DO % Sat.), chlorophyll-*a* (Chl-a, µg L^{-1}), fluorescent dissolved organic matter (fDOM, relative fluorescence units, RFU), inflow (m^3 s^{-1}), temperature difference (Temp Diff.) between the surface (0.1 m) and bottom (9 m), and buoyancy frequency (N^2). Highlighted boxes indicate environmental variables which were removed due to collinearity (rho>|0.70|).

		Minimum (μmol m^{-2} s^{-1})	Maximum (μmol m^{-2} s^{-1})	Median (μmol m^{-2} s^{-1})	Mean (μmol m^{-2} s^{-1})	Standard Deviation (μmol m^{-2} s^{-1})	Coefficient of Variation (%)
CH_4	Measured EC	-0.084	0.096	0.001	0.003	0.011	350.571
	Diffusive (Mean)	-0.0059	0.0928	0.0020	0.0048	0.0074	154.62
CO_2	Measured EC	-39.46	52.67	0.79	1.86	6.21	334.21
	Diffusive (Mean)	-1.24	17.50	0.11	0.38	1.22	325.66

Table S5. Minimum, maximum, median, mean, standard deviation, and coefficient of variation for measured methane (CH_4) and carbon dioxide (CO_2) fluxes for the study period (1 May 2020 to 30 April 2022) obtained from the eddy covariance (EC) system and mean diffusive fluxes. Mean diffusive fluxes represent all diffusive methods.

	25th Percentile	Median	75th Percentile	*p*-value
	CO_2 (μmol m^{-2} s^{-1})			
Day	-0.44	1.05	3.91	
Night	-0.60	1.03	3.48	0.093
Dawn	-0.07	1.34	4.37	
Dusk	-0.66	-0.03	0.65	<0.001
	CH_4 (μmol m^{-2} s^{-1})			
Day	-0.0017	0.0013	0.0079	
Night	-0.0016	0.0011	0.0066	0.162
Dawn	-0.0027	0.0002	0.0052	
Dusk	-0.0008	0.0014	0.0062	0.357
	Wind (m s^{-1})			
Day	0.92	1.27	1.73	
Night	0.76	1.03	1.44	<0.001
Dawn	0.95	1.24	1.64	
Dusk	0.87	1.23	1.67	0.003

Table S6. Diel (day/night) and dawn/dusk comparisons for measured eddy covariance (EC) fluxes for carbon dioxide (CO_2, μmol m^{-2} s^{-1}) and methane (CH_4, μmol m^{-2} s^{-1}) along with wind (m s^{-1}). Day corresponds to measurements collected from 11:00 to 13:00 while night corresponds to 23:00 to 01:00 throughout the time period. Dawn corresponds to measurements collected from 05:00 to 07:00 and dusk corresponds to 17:00 to 19:00. Statistically significant differences ($p < 0.05$) based on paired Wilcoxon sign-rank tests are highlighted in grey.

	Year 1	Year 2	Total Study Period
Mean Temp. (°C)	13.8	14.4	14.1
Min. Temp. (°C)	-9.93	-11.5	
Max. Temp. (°C)	35.1	35.0	
Mean Wind Speed ($m\ s^{-1}$)	2.00	1.97	1.99
Max. Wind Speed ($m\ s^{-1}$)	9.28	11.2	
Dominant Wind Direction (°)	191	199	198
Total Rainfall (mm)	1438	790	2228

Table S7. Various climatological variables calculated for Falling Creek Reservoir (FCR) for Year 1 (01 May 2020-30 April 2021), Year 2 (01 May 2021-30 April 2022), and the full study period calculated from the meteorological station deployed at the dam.

	Year 1	Year 2	Total Study Period
Mean Surface Temp. (ºC)	15.2	15.9	15.6
Min. Surface Temp. (ºC)	1.23	1.88	
Max. Surface Temp. (ºC)	31.4	31.3	
Mean Chl-a (µg L^{-1})	11.5	12.3	11.9
Min. Chl-a (µg L^{-1})	1.34	0.25	
Max Chla (µg L^{-1})	90.3	121	
Mean fDOM (RFU)	6.09	6.04	6.1
Min. fDOM (RFU)	3.19	3.01	
Max. fDOM (RFU)	10.4	8.79	
Mean % DO	107	97.8	102
Min. % DO	8.12	0	
Max. % DO	220	208	
Mean Inflow (m^3 s^{-1})	0.056	0.013	0.034
Min. Inflow (m^3 s^{-1})	0.005	0.006	
Max. Inflow (m^3 s^{-1})	0.27	0.20	

Table S8. Mean, minimum, and maximum calculated for key environmental variables from Falling Creek Reservoir during year 1 (May 2020 - April 2021) and year 2 (May 2021 - April 2022) including: Surface temperature, Chlorophyll-a (Chl-a), fluorescent dissolved organic matter (fDOM, RFU), percent dissolved oxygen (% DO), and inflow.

GHG	Order	AR(1)	MA(1)	MA(2)	Temp. Surf. (ºC)	% DO Sat.	Chl-a (µg L^{-1})	fDOM (RFU)	Flow (m^3 s^{-1})	Thermo. (m)	AICc	RMSE
	Daily											
CO_2	(1,0,0)	0.11			0.18		-0.17	0.07	0.08	-0.09	1281.69	0.97
S.E.		0.05			0.07		0.06	0.05	0.05	0.05		
CO_2	(1,0,0)	0.10			0.20	-0.07	-0.14	0.07	0.12	-0.09	1281.79	0.97
S.E.		0.05			0.07	0.05	0.06	0.05	0.06	0.05		
CO_2	(0,0,2)		0.11	0.05	0.20		-0.17		0.08	-0.09	1282.98	0.97
S.E.			0.05	0.05	0.07		0.06		0.05	0.05		
CO_2	(0,0,2)		0.10	0.04	0.22	-0.07	-0.15		0.11	-0.09	1283.35	0.97
S.E.			0.05	0.05	0.07	0.05	0.06		0.06	0.05		
CH_4	(0,0,0)				0.27			0.12		0.25	1213.36	1.02
S.E.					0.05			0.05		0.05		
CH_4	(0,0,0)				0.28	-0.04		0.12		0.25	1214.53	1.02
S.E.					0.05	0.04		0.05		0.05		
CH_4	(0,0,0)				0.28		0.02	0.12		0.25	1215.30	1.02
S.E.					0.07		0.06	0.05		0.05		

GHG	Order	AR(1)	MA(1)	MA(2)	Temp. Surf. (ºC)	% DO Sat.	Chl-a (µg L^{-1})	fDOM (RFU)	Flow (m^3 s^{-1})	Thermo. (m)	AICc	RMSE
	Weekly											
CO_2	(0,0,0)				0.64	-0.16		0.13	0.20	-0.19	183.00	0.63
S.E.					0.07	0.07		0.07	0.08	0.07		
CO_2	(0,0,0)				0.67	-0.17			0.19	-0.20	184.05	0.64
S.E.					0.07	0.07			0.08	0.07		
CH_4	(0,1,1)		-0.75		0.36			0.23	-0.36	0.24	184.13	0.64
S.E.			0.09		0.15			0.10	0.13	0.08		
CH_4	(0,1,1)		-0.65					0.28	-0.43	0.21	185.88	0.65
S.E.			0.09					0.11	0.15	0.08		
	Monthly											
CO_2	(0,0,0)				0.73			0.24		-0.31	42.58	0.48
S.E.					0.10			0.10		0.10		
CO_2	(0,0,0)				0.71	0.15		0.27		-0.32	43.55	0.45
S.E.					0.10	0.10		0.10		0.10		
CO_2	(0,0,0)				0.73			0.27	0.15	-0.26	43.88	0.46
S.E.					0.10			0.10	0.10	0.10		
CH_4	(0,0,1)		0.72		0.74				-0.26	0.21	38.85	0.41

S.E.			0.18		0.14				0.12	0.07		

Table S9. Best-fit results from Autoregressive Integrated Moving Average (ARIMA) showing the top selected model (lowest corrected Akaike Information Criterion, AICc < 2). Models are separated by greenhouse gas (GHG) flux as carbon dioxide fluxes (CO_2) and methane fluxes (CH_4) as well as by timescale (daily, weekly, monthly). Environmental predictors included: Surface temperature (Surface Temp, °C), dissolved oxygen saturation (DO Sat, %), Chlorophyll-*a* (Chl-a, μg L^{-1}), fluorescent dissolved organic matter (fDOM, RFU), inflow discharge (Inflow, m^3 s^{-1}), and thermocline depth (Thermo. depth, m). Model order is specified as (p,d,q) where p is the order of the AR term, d is the order of the integration term, and q is the order of the MA term. Results for all models with 2 AICc of the best fitting model are included. The root mean square error (RMSE) is also reported for each model. Shaded model results are included in the main manuscript (Table 1). S.E. is the standard error.

	25th Percentile	Median	75th Percentile	p-value
	CO_2 (µmol m^{-2} s^{-1})			
Intermittent ice-on (Year 1)	0.12	0.71	1.34	<0.001
Continuous Ice-on (Year 2)	-0.34	0.28	0.93	
	CH_4 (µmol m^{-2} s^{-1})			
Intermittent ice-on (Year 1)	-0.001	0.001	0.004	<0.001
Continuous Ice-on (Year 2)	-0.002	-0.001	0.000	

Table S10. 25th percentile, median, and 75th percentile reported measured eddy covariance (EC) data for carbon dioxide (CO_2, µmol m^{-2} s^{-1}) and methane (CH_4, µmol m^{-2} s^{-1}) fluxes during winter 2020-2021 (year 1) under partial ice-on ('On') and during winter 2021-2022 (year 2) under continuous ice-on. The Mann-Whitney-Wilcoxon test was used to identify medians which were statistically different. Statistically significant relationships are highlighted in grey.

	Season	CO_2 (μmol m^{-2} s^{-1})		CH_4 (μmol m^{-2} s^{-1})		Wind (m s^{-1})	
		Mean	***p*-value**	**Mean**	***p*-value**	**Mean**	***p*-value**
Day	Spring	1.02		0.000		1.19	
Night	Spring	0.82	0.77	0.001	0.57	0.97	0.01
Day	Summer	2.98		0.006		1.30	
Night	Summer	3.14	0.07	0.004	0.12	0.97	<0.001
Day	Fall	0.79		0.005		1.30	
Night	Fall	0.61	0.86	0.002	0.13	1.09	0.005
Day	Winter	0.68		-0.001		1.26	
Night	Winter	0.61	0.32	0.000	0.03	1.23	0.10
Dawn	Spring	1.32		0.000		1.28	
Dusk	Spring	-0.25	<0.001	0.000	0.06	1.30	0.05
Dawn	Summer	3.55		0.005		1.19	
Dusk	Summer	-0.33	<0.001	0.005	0.24	1.08	0.002
Dawn	Fall	1.28		0.003		1.19	
Dusk	Fall	0.10	0.002	0.004	0.48	1.43	0.76
Dawn	Winter	0.70		-0.002		1.35	
Dusk	Winter	0.19	<0.001	0.000	0.04	1.31	0.07

Table S11 Diel (day/night) and dawn/dusk comparisons for measured eddy covariance (EC) fluxes for carbon dioxide (CO_2, μmol m^{-2} s^{-1}) and methane (CH_4, μmol m^{-2} s^{-1}) along with wind (m s^{-1}) for each season (Spring, March-May; Summer, June-August; Fall, September-November; Winter, December-February). Day corresponds to measurements collected from 11:00 to 13:00 while night corresponds to 23:00 to 01:00 throughout the time period. Dawn corresponds to measurements collected from 05:00 to 07:00 and dusk corresponds to 17:00 to 19:00. Statistically significant differences ($p < 0.05$) based on paired Wilcoxon sign-rank tests are highlighted in grey.