New insights into diel to interannual variation in carbon dioxide emissions from lakes and reservoirs

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Abstract

Accounting for temporal changes in carbon dioxide (CO_2) emissions from freshwaters remains a challenge for global and regional carbon budgets. Here, we synthesize 171 site-months of eddy covariance flux measurements of CO_2 from 13 lakes and reservoirs in the Northern Hemisphere (NH) and quantify the magnitude and dynamics at multiple temporal scales. We found pronounced diel and sub-monthly oscillatory variations in CO_2 flux at all sites. Diel variation converted sites to daily net sinks of CO_2 in only 11% of site-months. Upscaled annual emissions had an average of 25% (range 3-58%) interannual variation. Given temporal variation remains under-represented in inventories of CO_2 emissions from lakes and reservoirs, revisions in CO_2 flux are needed using a better representation of sub-daily to interannual variability. Constraining short- and long-term variability is necessary to improve detection of temporal changes of CO_2 fluxes in response to natural and anthropogenic drivers.

Plain Language Summary

Lakes and reservoirs around the world are likely a major component of the global carbon cycle. Recent syntheses of measurements find their contributions to be on the order of 2-6% of total global fossil fuel emissions. However, these estimates are primarily derived from compilations with low frequency of sampling, from a few times a year up to weekly, often restricted to a single season, and with limited regard to year-to-year variations. Here, we conduct the first analysis of a globally distributed network of sub-hourly, multi-year lake and reservoir carbon dioxide emissions. These measurements were made using eddy-covariance flux towers, which continuously sample these emissions year-round. Across our 13 study sites, we found nighttime emissions regularly exceeding daytime emissions and persistent sub-monthly oscillations regardless of lake size or nutrient status. For sites with multiple years of data, we found an average 25% variation in estimated annual emissions depending on the year chosen. Together, these results point to a need for improved, systematic sub-weekly sampling of freshwater systems to better understand dynamics of freshwater ecosystems, reduce uncertainty in landscape to global carbon budgets, and project changes to atmospheric greenhouse gas burdens in a warming climate.

Index terms (5): 0428 Carbon cycling, 0426 Biosphere/atmosphere interactions, 0438 Diel, seasonal, and annual cycles, 0434 Data sets, 0458 Limnology

Keywords (6): eddy covariance; freshwater systems; lakes; reservoirs; carbon flux; synthesis

Key Points:

- First synthesis of high-frequency aquatic freshwater carbon dioxide flux observations reveals large diel, sub-annual, and interannual variation
- At all sites, nighttime emissions are larger than daytime, sub-monthly oscillations are present, and year-to-year variation averaged 25%
- Under-sampling of these dynamics leads to potential bias in estimates of contribution of freshwater systems to the global carbon cycle

1. Introduction

The global carbon budget is rapidly changing in response to human emissions, climatic modes of variability, and global changes (Friedlingstein *et al*., 2020; Hanson *et al*., 2006). Prior studies have estimated that 0.14-0.64 Pg C-CO_2 is annually released to the atmosphere through lakes and reservoirs (Aufdenkampe *et al*., 2011; Ciais *et al*., 2013; Cole *et al*., 1994, 2007; Drake *et al*., 2018; Holgerson *et al*., 2016; Raymond *et al*., 2013), offsetting 10-40% of the global terrestrial land sink. However, most of these estimates are made with relatively limited sampling, generally constrained to the open-water or summer season during the daytime, and with limited consideration of interannual and shorter-scale variation (Butman *et al*., 2018; Ran *et al*., 2021).

Underrepresentation of temporal CO_2 flux variability in existing CO_2 flux inventories may bias estimates of lake CO_2 emissions (Deemer *et al*., 2016; Klaus *et al*., 2019). For example, recent studies have found nighttime emissions exceeding daytime emissions or uptake in reservoirs (Liu *et al*., 2016) and rivers (Gómez-Gener *et al*., 2021**)**. A lack of frequent and long-term CO_2 observations also limits our ability to differentiate natural CO_2 flux variations from the consequences of anthropogenic perturbations to freshwater biogeochemistry and predict future CO_2 responses to the global change (Hasler *et al*., 2016). Decadal-scale time series that capture sub-annual variability of the CO_2 flux remain rare (Finlay *et al*., 2019; Huotari *et al*., 2011). Traditional in-situ aquatic sampling methods for CO2 concentrations and derived fluxes in natural and artificial freshwaters also come with high uncertainty (Baldocchi *et al*., 2020; Golub *et al*., 2017).

Advances in the past several decades, however, have enabled more long-term, continuous high-frequency (hourly) measurements in freshwater ecosystems, which are capable of capturing the dynamics of air-water fluxes at time scales of hours to years (Eugster *et al*., 2003; Huotari *et al*., 2011; Morales-Pineda *et al*., 2014). At these time scales, CO_2 fluxes have been shown to respond to variations in wind speed and direction (Podgrasjek *et al*., 2015), carbonate equilibria (Atilla *et al*., 2011), ecosystem metabolism (Provenzale *et al*., 2018), convective mixing (Eugster *et al*., 2003; Mammarella *et al*, 2015), internal waves (Heiskanen *et al*., 2014), ice phenology (Reed *et al*., 2018), and hydrological and carbon inflows (Rantakari *et al*., 2005; Weyhenmeyer *et al*., 2015). These sources of variation may be overlooked by low-frequency and season-restricted sampling that dominate freshwater science (Desai *et al*., 2015).

Many previous studies were conducted using eddy covariance (EC) flux towers, which have gained prominence for use in freshwaters (Vesala *et al*., 2012). The eddy covariance method directly measures air-water CO_2 fluxes within an ecosystem-scale footprint (Vesala *et al*., 2006). While its application over lakes has mostly covered short periods of time (e.g., Eugster *et al*., 2003; Podgrajsek *et al*., 2015; Vesala *et al*., 2006), an increasing number of sites are now measuring lake-atmosphere fluxes continuously over multiple years (Franz *et al*., 2016; Huotari *et al*., 2011; Mammarella *et al*, 2015; Reed *et al*., 2018).

This recent growth of continuous measurements affords an opportunity to investigate the relative magnitude and importance of diel to interannual variation in lake and reservoir exchanges and discuss pathways to incorporating these insights into improving quantification of freshwaters in the global carbon cycle. Here, we quantify diel to inter-annual dynamics of CO_2 fluxes, directly measured by eddy covariance from 13 lakes and reservoirs representing a broad nutrient-humic spectrum of sites in the Northern Hemisphere. Our main aim was to identify modes of CO_2 flux variability missed by infrequent sampling that may lead to biases in estimates of annual CO_2 flux from lakes and reservoirs.

2. Materials and Methods

2.1 Study sites

Data on air-water CO_2 exchange and meteorological drivers were acquired from study sites across the Northern Hemisphere with at least one season of observations between 2005-2015, of which 13 were retained here for analysis (Table 1 and S1). The remaining submitted sites were withheld for challenges in meeting uncertainty and gap filling criteria (see Supplemental Methods). This analysis represents the largest synthesis of lake and reservoir eddy-covariance CO_2 flux observations to-date. These sites were collected based on organization of a workshop (Desai *et al*., 2015) and an open call through listservs. Selected sites included 9 lakes and 4 reservoirs, mostly located between 40-68°N latitude, coinciding with the largest area of Earth's covered with lakes. Most sites had data available over multiple seasons, but only a few also had measurements during winter ice cover. Lake area ranged from 0.036 km^2 to 623 km^2 (median: 15.2 km^2), with median mean depth of 6 m (range: 0.6 to 11 m); most developed a seasonal thermocline and were dimictic or monomictic (Table S1). Two water bodies had a significant fraction of submerged and emergent macrophytes (SE-Tam and DE-Zrk) within the footprint of the flux tower.

2.2 Measurements

The eddy covariance technique directly measures the exchange of momentum, heat and matter (water vapor, CO_2, or other trace gases) at the air-water interface and is considered the most direct method of measuring surface exchanges with the atmosphere (Vesala *et al.*, 2006). The measured fluxes are integrated across the EC flux footprint (i.e., the upwind area "seen" by the tower), capturing all sources and sinks of turbulent exchanges. The flux towers were located on floating platforms, lake shoals or islands, or on shore depending on the site (Table S1). The high frequency (10 or 20 Hz) measurements were made with open-path or closed-path infrared gas analyzers and processed into half-hourly average fluxes by site PIs according to standard methods (Aubinet *et al*, 2012). The towers were additionally equipped with instruments providing half-hourly to hourly measurements of biophysical variables (e.g. net radiation, air temperature and humidity, photosynthetically-active radiation (PAR), 2-D wind direction and speed, water temperature, aquatic CO_2 or O_2 concentration, water level), although data availability and frequency varied among the sites. Data were harmonized to uniform formats and units, screened for fetch, and de-spiked using a common flux post-processing standard (Pastorello *et al.*, 2020) to reduce cross-site flux uncertainty due to methodological differences. All data were submitted to the Environmental Data Initiative repository (Golub *et al.*, 2021).

2.3 Flux data processing

After despiking and quality control, the half-hourly averages of CO_2 fluxes retained 3-90% of observations during measurement periods (Table S1). A larger fraction of gaps relative to terrestrial systems were caused by the exclusion of out-of-lake and mixed tower footprints and flagging by quality control algorithms applied to flux computation. Despite these gaps, the available data provide an unprecedented number of direct CO_2 flux observations (171 site-months and 3,832 site-hours in total) that captured flux variability at multiple time scales (i.e. diel and seasonal) that are usually poorly represented in traditional limnological studies. For further analysis, all quality-controlled flux observations were identified, with missing observations gap-filled, uncertainty assessed for each time point, and continuous flux time series aggregated for diel, seasonal (sub-annual), and annual estimates.

Flux data were gap-filled using marginal distribution sampling (MDS) (Reichstein *et al*., 2005) within REddyProc (Wutzler *et al*., 2018). The MDS approach, which applies both a moving window and look-up table multiple imputation approach, used observations of shortwave incoming radiation, air temperature, and vapor pressure deficit (VPD) to fill data gaps.

The CO_2 uncertainty measured with the EC approach exhibits a variety of systematic and random errors, several of which can be quantified (Richardson *et al*., 2012; Rannik *et al*, 2016). Random errors in half-hourly averages of CO_2 flux over lakes can range from 26% to 40%, with uncertainty more pronounced in eutrophic systems (Jammet *et al*., 2017; Mammarella *et al*., 2015). The uncertainty in half-hourly flux averages was estimated as the standard deviation of observations used for gap-filling with the MDS algorithm.

The mean diel change of CO_2 and associated uncertainty was calculated by deriving the average and one standard deviation from all observations within the same month for each half-hour of the day. Lake-months with <15 observations per half-hourly average were discarded to avoid influences of unreliable means on calculated statistics. The monthly-averaged flux amplitudes were calculated as a difference between 95th percentile of nighttime observations (when shortwave incoming radiation was <10 W m^{-2}) and 5th percentile of daytime observations (>10 W m^{-2}).

Daily CO_2 flux values were calculated by averaging the 48 half-hourly fluxes. Daily CO_2 flux observations were binned according to Sturge's formula (i.e. log2(N)+1 where N represents the number of observations per lake) to accurately represent frequencies of flux distribution. To avoid the influence of extreme outliers on bin resolution, the bins were scaled to >1^{st} and <99^{th} percentiles. Annual CO_2 flux sums were calculated for the duration of ice-free season by summing daily fluxes. The ice-free period was determined from observational ice-on and ice-off data or predicted from 0.5°x0.5° gridded mean monthly air temperature (2000-2010) at a given latitude (Wei *et al*., 2014). All but two sites (US-RBa and LA-NT2) had seasonal ice cover.

2.4 Data analysis

We analyzed the half-hourly CO_2 fluxes and three major groups of biophysical covariates. The first group included variables related to wind forcing acting on the water surface (i.e. friction velocity, wind speed, momentum flux). The second group encompassed the variables related to temperature cycles and proxies of energy in the system (i.e. air temperature, water temperature, ΔT (T_{water}-T_{air}), sensible and latent heat fluxes). The last group included the variables associated with solar radiation -- proxies for primary productivity (i.e. ΔpCO_2 (ΔpCO_{2water}- ΔpCO_{2air}), PAR). Variables were included if they were measured at the site (Table S1). The robust linear least-squares second-order polynomial model with bisquare weighting method was used to compare bivariate relationships across lakes. To estimate confidence intervals around estimated parameters and curves, we bootstrapped residuals with 1,000 iterations. The analyses were performed with MATLAB ver. R2018a using Curve Fitting Toolbox. To determine the standardized difference between two means with repeated unpaired measurements and imbalanced population sizes, we used the Cohen's d test. The mean difference between the mean daily CO_2 fluxes was divided by the pooled variance. A coefficient d of 0.20, 0.50, 0.80 indicates small, medium, and large differences, respectively. One macrophyte-covered reservoir with distinct fluxes is provided in the Supplemental Materials.

3. Results

3.1 Magnitude of CO_2 fluxes from lakes and reservoirs

Study sites represented a wide range of nutrient-color statutes and physical characteristics of water bodies, and as a result spanned a range of daily CO_2 fluxes, though with some common elements (Fig. 1). The mean daily CO_2 flux across all sites was 0.43±0.34 µmol m^{-2} s^{-1} (range: -

0.075 to 1.25 µmol m^{-2} s^{-1}) with only 6% of observations indicating neutral fluxes or net CO_2 uptake. The spread of time-resolved fluxes varied 102-798 % of the site-specific daily mean (Fig. 1). Reservoirs had smaller but more variable fluxes relative to the lakes (0.32±0.71 vs. 0.41±0.31 µmol m^{-2} s^{-1}), though the reservoir sample size is smaller and more geographically restricted. Two thirds of sites had at least 66% of daily fluxes within the cross-site flux mean ±1 SD (Cohen's d: $0.02<d<0.76$).

3.2 Temporal variability of CO_2 fluxes from lakes and reservoirs

Averaged diel CO_2 curves had regular patterns of daytime minima and nighttime maxima across all sites in most months (Fig. 2a). Daytime hourly fluxes were on average 35% (range: 7-60%) lower than nighttime fluxes, though in 94% of site days, those were still net positive emissions. Despite the commonly observed daytime CO_2 flux dip, the flux decrease was large enough to convert our sites to daily net sinks of CO_2 in only 11% of site-months (Fig. 2a, Table 1). The mean uncertainty of diel CO_2 was strongly influenced by extreme observations, with 192% mean uncertainty, but only 79% median uncertainty (Fig. 2b).

Maximum diel flux amplitudes typically occurred in July and August and ranged 0.24-1.09 µmol m^{-2} s^{-1}. Relative to the summer amplitudes, shoulder season CO_2 flux amplitudes were on average 44-49% smaller in May and September and 26-37% in April and October. Diel variation was negligible at both ends of the ice-free season (Fig. 2a).

Monthly to seasonal CO_2 flux variability was nearly twofold compared to diel flux variation (Table 1). Surprisingly, we found frequent sub-monthly (20-30-day) oscillations across all water bodies, regardless of the system's physical or biogeochemical conditions (Fig. 3a). While most site-level oscillations fluctuated around the CO_2 flux averages, for some, amplitudes scaled with flux minima and maxima (Fig. S1).

Sites with multi-year data had relatively consistent sub-annual patterns across years, although the timing and amplitudes of sub-monthly oscillations varied among lake-years. When integrated over time-resolved daily CO_2 fluxes, both sub-monthly and sub-annual modes of variability accounted for two thirds of the site-level daily CO_2 flux variability (range 10-190%). Mean and median uncertainty were 167% and 67% of mean daily CO_2 flux, respectively (Fig. 3b).

Once scaled to ice-free season annual emissions, and assuming zero fluxes during ice cover, we found all water bodies were net sources of CO_2, despite missing any ice off/on related fluxes (Table 1). The cross-site mean and standard deviation of 23 site-years was 95±49 gC m^{-2} yr^{-1} (range: 14-224 gC m^{-2} yr^{-1}). Inter-annual variability (IAV) was calculated as a standard deviation of annual CO_2 flux for each site with multi-year data. The mean cross-site IAV was 22 gC m^{-2} yr^{-1} (25%) and ranged 4-44 gC m^{-2} yr^{-1} (3-58%).

3.3 Drivers of CO_2 fluxes from lakes and reservoirs

While the continuous data allowed capturing CO_2 fluxes variability at different temporal scales, we still had a limited capacity to attribute which factors and processes governed the observed patterns of CO_2 flux. We found small standardized differences between CO_2 fluxes among site groups belonging to the three humic states ($d<0.01$), medium differences between oligotrophic and eutrophic states ($d=0.24$), and large CO_2 differences between mesotrophic and oligotrophic states ($d=0.66$), and between mesotrophic and eutrophic states ($d=0.72$) (Fig. 4). Commonly observed biophysical covariates explained an average of 32% of variance in half-hourly CO_2 fluxes (Fig. 4g). Wind-related variables were identified as key to explaining CO_2 flux variability in eight out of 13 sites. Biophysical variables related to exchanges of heat at the air-water interface, particularly air-water temperature difference (ΔT) and turbulent energy exchange (latent and sensible heat fluxes) correlated with CO_2 flux. The fitted regressions were non-linear and highly variable across sites, owing to ecosystem differences and presence of confounding factors (e.g. differential responses to co-dependent covariates).

4. Discussion

4.1 Unresolved temporal variation in CO2 fluxes

We demonstrated that CO_2 fluxes from lakes and reservoirs exhibited significant and consistent variability at diel to (inter)-annual scales, which could comprise unresolved sources of uncertainty or bias in current estimates of annual CO_2 fluxes from infrequent and season-restricted sampling. Though our study lakes were not randomly selected and cannot be directly used to upscale (Stanley *et al*., 2019), they were broadly reflective of common mid-latitude freshwater systems in a broad range of humic-status and mixing regimes. Additional considerations for sampling across lake size and catchment area (Hanson *et al*., 2007; Holgerson *et al*., 2016) and hydrological setting (Jones *et al*., 2018) would be required to design a representative estimate for global upscaling.

Instead, we were able to investigate the role of temporal variation on a range of systems that broadly reflect many lakes and reservoirs. Our reported continuous daily fluxes corresponded with the upper end (88th percentile) of previously published flux magnitudes (Tables S2). The observed temporal variation suggests that infrequent and time of day or year scheduling restricted sampling may add a significant source of underestimation bias in existing inventories of CO_2 fluxes from lakes and reservoirs of similar type and size (Klaus *et al*., 2019).

In particular, we note significant diel variation found in all study sites, with routinely higher emissions at night, consistent with a recent study over rivers (Gómez-Gener *et al*., 2021). The diel reduction of dissolved CO_2 concentrations and fluxes are often associated with ecosystem metabolism (Hanson *et al*., 2003) and was supported by negative correlations with PAR (Fig. 4g). Water temperature (Provenzale *et al*., 2018), carbonate equilibria fluctuations (Atilla *et al*., 2011), water-side convection (Mammarella *et al*, 2015; Podgrajsek *et al*., 2015), and internal waves (Heiskanen *et al*., 2014) can additionally govern diel CO_2 dynamics. Our observed diel amplitudes were within 21-43% of sub-hourly flux amplitudes derived from dissolved CO_2 concentrations (Hanson *et al*., 2003; Morales-Pindea *et al*., 2014) or previously published EC-measured fluxes (Liu *et al*., 2016; Vesala *et al*., 2006). Our results support the notion that existing global lake carbon budgets are underestimates of net emissions.

We also found common sub-monthly modes of CO_2 flux variability across all of our sites. Similar oscillations in the continuous observations have been reported for dissolved CO_2 (Atilla *et al*., 2011; Huotari *et al*., 2009; Morales-Pineda *et al*., 2014; Vachon and del Giorgio, 2014) and CO_2 fluxes (Franz *et al*., 2016), indicating the prevalence of oscillatory patterns in CO_2 time series at both sides of the air-water interface. Oscillations have previously been attributed to the interplay of wind forcing (Liu *et al*., 2016), upwellings of CO_2-rich waters (Morales-Pineda *et* *al*., 2014), biologically-driven (metabolic and trophic) changes in carbonate equilibria (Atilla *et al*., 2011), convective mixing (Huotari *et al*., 2009) and water temperature (Atilla *et al*., 2011). However, this is the first study to find a consistent pattern in a wide range of systems, regardless of size. We also observed changes to the prevalence of underlying sub-monthly CO_2 flux oscillations through the year at several sites, likely reflecting seasonal ecosystem changes, such as spring/fall turnover (Baehr *et al*., 2004), radiative and heat exchanges (Heiskanen *et al*., 2014), and hydrological inflows (Vachon *et al*., 2017).

4.2 Implications for the global carbon budget

After our daily fluxes were scaled to annual totals, our estimates of annual CO_2 emissions were in the upper end reported for lakes and reservoirs (Table S2). All systems were sources of CO_2 in most years, though there have been sites that reported significant carbon sinks (e.g., Shao *et al*. 2015; Reed *et al*., 2018) and additional propagation of uncertainty from data gap filling and filtering (e.g., of nighttime uptake) can push some of our study sites toward sinks, though weakly. While our lakes are not fully representative for all lakes on Earth, we postulate that improved temporal resolution of site-level CO_2 fluxes is one of the sources of differences between this study and published annual fluxes (Table S2). The results also imply that a proposed recommended number of samples per year (4-8) (Klaus *et al*., 2019; Natchimuthu *et al*., 2017) is likely insufficient to constrain annual CO_2 fluxes from lakes and reservoirs. Rather, approaches to increase nighttime samples and open-water season weekly or higher-frequency sampling would increase the accuracy of annual estimates, given our observed diel and sub-monthly variations.

Additionally, sites with multiple years of data all showed non-trivial interannual variation. The estimate of average interannual variability of CO_2 fluxes (25%) is modest compared to that (88%) observed in terrestrial ecosystems (Baldocchi *et al*., 2018), probably reflecting the lower number and diversity of ecosystems with multi-year measurements or more buffering against climate extremes by large water bodies. However, given that CO_2 flux from freshwaters positively scales with the productivity of terrestrial ecosystems at shorter time-scales (Butman *et al*., 2016; Hastie *et al*., 2018; Walter *et al*., 2021), it is possible that the interannual variation of carbon displaced from land will propagate onto CO_2 outgassed through freshwaters (Drake *et al*., 2018; McDonald *et al*., 2013), providing a possible pathway to constrain freshwater interannual variability. Neglecting this variation is an additional source of bias in our current view on global CO_2 emissions from lakes and reservoirs (Fig. 4).

Given that EC CO_2 fluxes are affected at both sides of the air-water interface (Wanninkhof *et al*., 2009), a better constraint of the contribution of lakes to the global carbon cycle will also require reporting and synthesis of additional continuous waterside data (e.g. temperature, dissolved CO_2 and O_2), site-level ecosystem characteristics (e.g. nutrient-color legacies, ecosystem metabolism, and aquatic vegetation such as algae) and sampling an increased site diversity within climatic zones (Lehner and Döll, 2004). With more frequent air and aquatic observations, we will better constrain CO_2 fluxes at different time scales, assess the prevalence of temporal patterns in CO_2 fluxes, and reduce uncertainty in eddy flux measurements over freshwaters (e.g., Ejarque *et al*., 2021). Such work will be needed to quantify and evaluate landscape (Buffam *et al*., 2011; Zwart *et al*., 2018) to global (DelSontro *et al*., 2018) carbon budget components from lakes and reservoirs.

5. Conclusions

Across 13 study sites with EC flux observations, on average all lakes and reservoirs were net annual sources of CO_2 to the atmosphere. However, the time series unraveled large diel to (sub)-monthly oscillatory CO_2 patterns across sites, among a broad range of biogeochemical and physical site characteristics. These modes of variability accounted for two thirds of daily and a quarter of annual CO_2 flux variation, with sub-annual variability dominating over diel and inter-annual flux variabilities. After integrating these modes of variability into time-resolved fluxes, the CO_2 flux estimates were at the upper end of published CO_2 emissions for lakes and reservoirs. Our results support the idea that long-term, continuous, sub-weekly or sub-daily measurements of carbon dynamics in freshwater aquatic systems are necessary to detect long-term trends of lake carbon fluxes. Long-term, frequent measurements of lake fluxes are also needed to attribute natural and anthropogenic drivers to ecosystem changes that influence the global carbon cycle and its future projections. We advocate for establishing and maintaining a long-term observation network that combines EC flux measurements with highly detailed site-specific carbon budget studies over key lake and reservoir ecosystems representing broader geographical gradients.

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Open Research

We have deposited all eddy covariance lake observations and gap-filled values in the Environmental Data Initiative repository at: https://environmentaldatainitiative.org/ and a DOI will be provided once available, prior to acceptance. In the interim, reviewers can access all original and gap-filled flux data are available at: http://co2.aos.wisc.edu/data/lakeflux/synthesis/

or this staging site: https://portal-s.edirepository.org/nis/mapbrowse?scope=edi&identifier=835&revision=1 . Several sites are also accessible from Fluxnet affiliated archives as noted in Table S2.

Author Contribution Statement

M.G. designed experimental protocol and conducted the data syntheses. A.R.D and M.G. wrote the manuscript. T.V., I.M., G.B., and G.W. supervised research, contributed observations, and edited the manuscript. All other authors contributed with flux observations and commented on the manuscript.

Competing Financial Interests

The authors declare no competing financial interests.

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Figures

Fig. 1. Normalized histograms of daily CO_2 fluxes over ice-free season in nine lakes and four reservoirs, showing that all studied ecosystems emitted CO_2 to atmosphere in the majority of site-days. Vertical solid lines and their numerical representation indicate mean daily CO_2 flux. Shaded areas show observations with negative CO_2 flux, which by convention, indicate net CO_2 uptake.

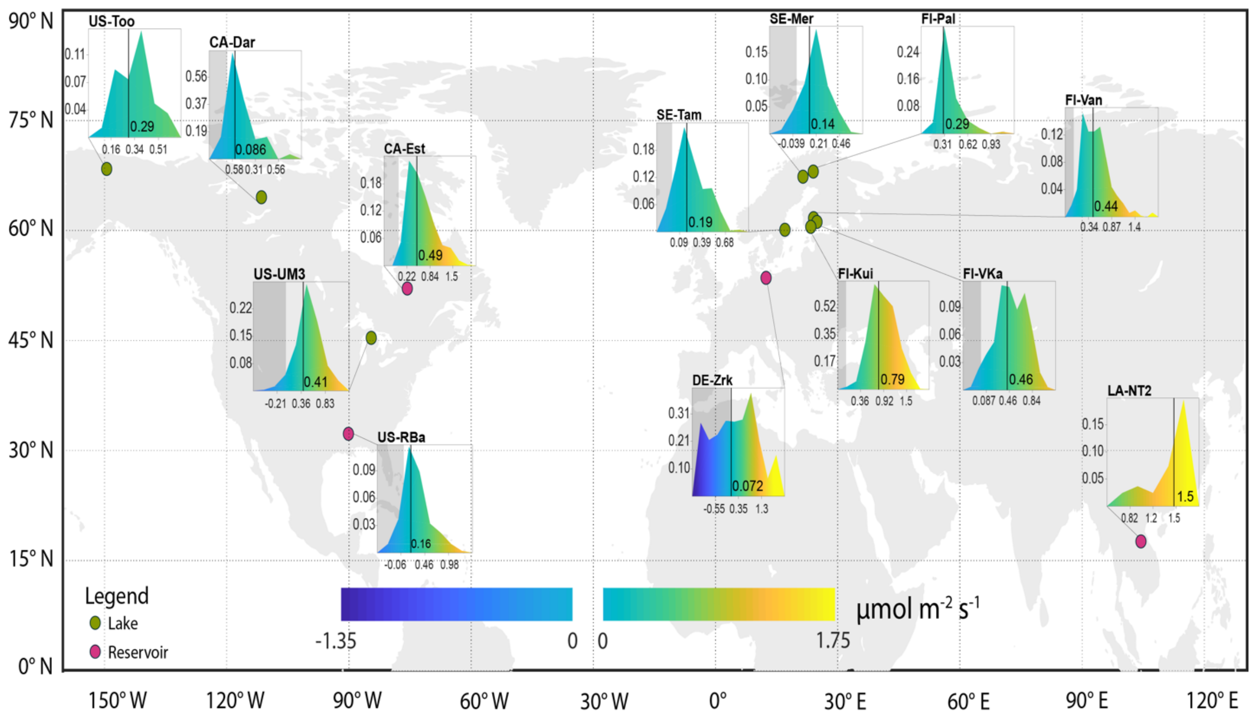


Fig. 2. a) Mean diel course of CO_2 fluxes across site-months (May-October) and site-years and b) associated uncertainty (one standard deviation of monthly-averaged half-hourly observations show consistent patterns of daytime flux reduction. Lines represent 6-hour moving average. Negative fluxes indicate net CO_2 uptake. Note separate flux scale for the macrophyte reservoir.

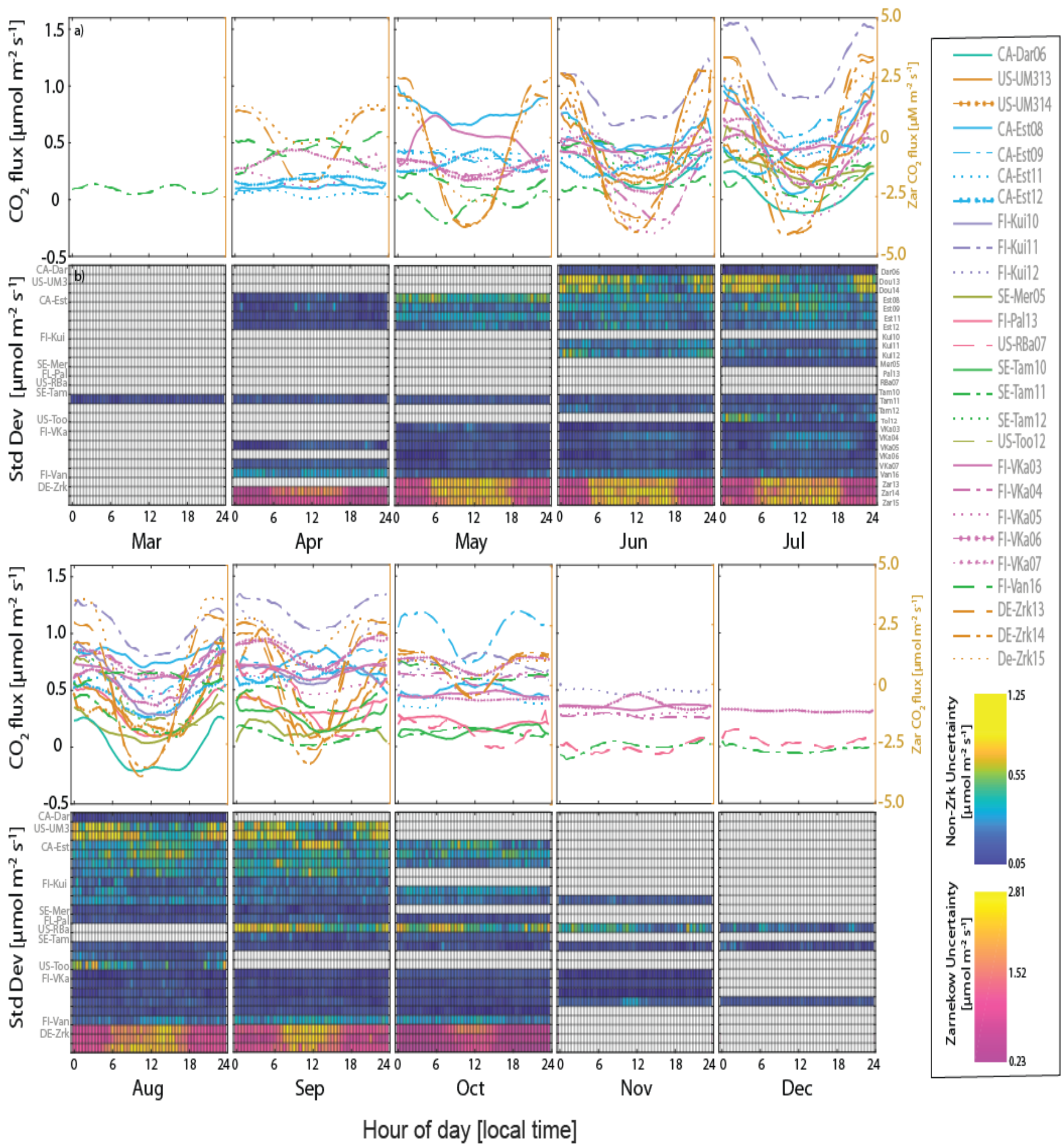


Fig. 3. a) Seasonal evolution of daily CO_2 fluxes across site-years and b) associated uncertainty (one standard deviation of daily values) indicate frequent sub-monthly oscillations across water bodies. Negative fluxes indicate net CO_2 uptake. Note separate flux scale for two reservoirs. Lines represent 10-day moving averages.

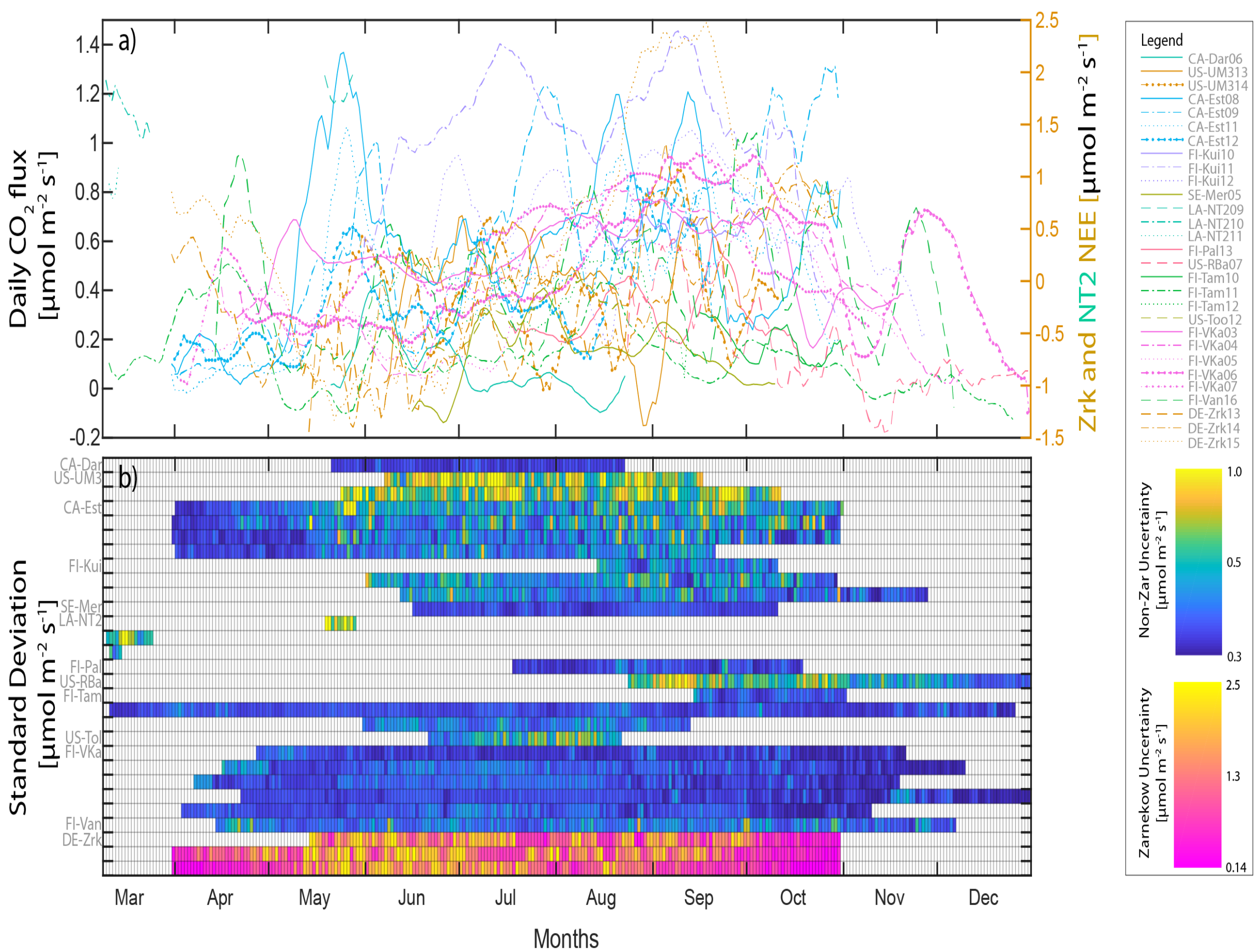
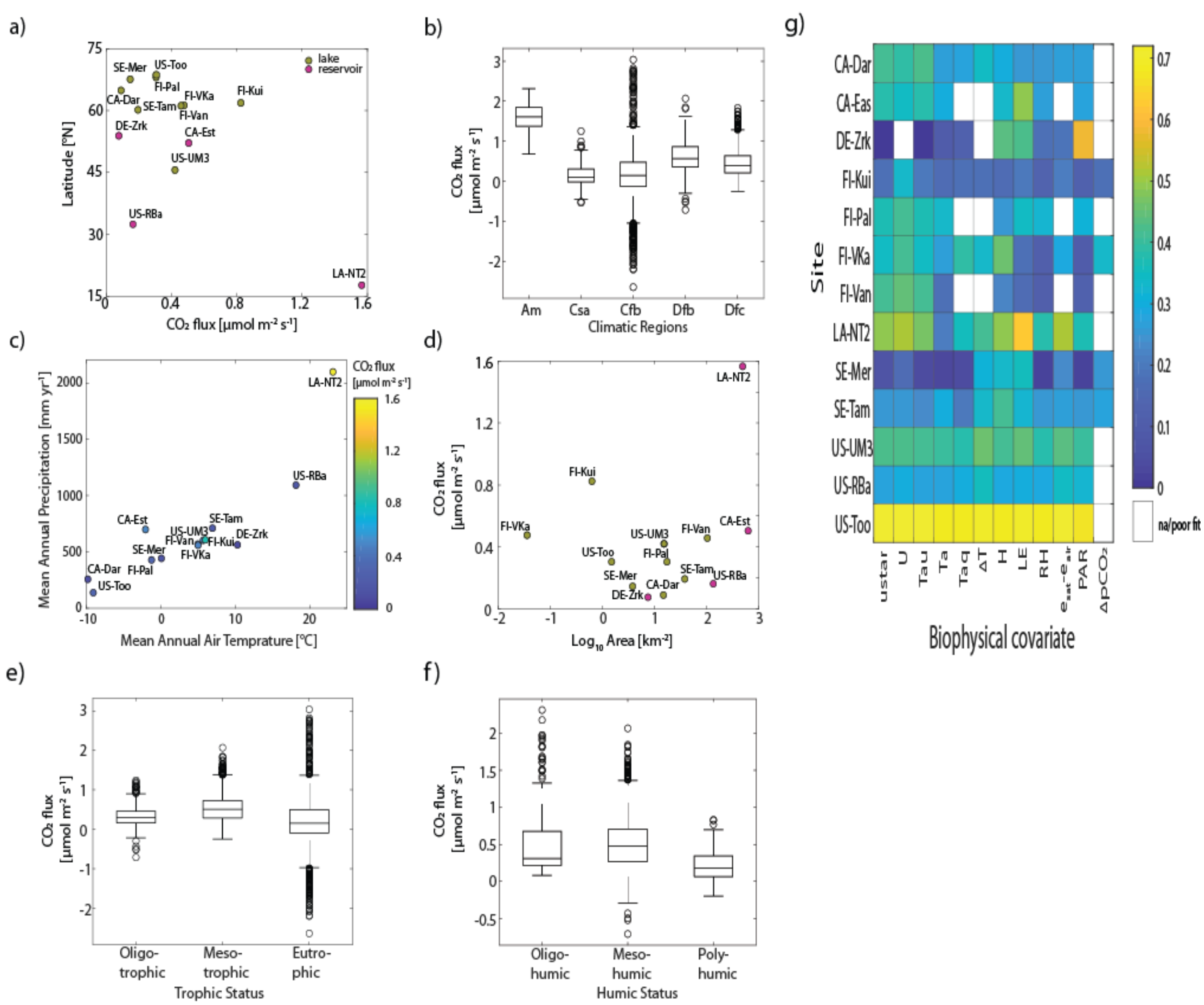


Fig. 4 Relationships of the mean daily CO_2 flux across a) latitude gradient, b) Koeppen-Geiger climatic zones, c) mean annual temperature and precipitation (2000-2010), d) surface area, e) trophic status, and f) color status. g) Pearson correlation (r2) of daily flux against biophysical covariates of friction velocity (ustar), wind speed (U), momentum flux (Tau), water temperature (Taq), air-water temperature gradient (DeltaT), sensible heat flux (H), latent heat flux LE), relative humidity (RH), vapor pressure deficit (E_{sat}-e_a), photosynthetic active radiation (PAR), and pCO_2 air-water gradient (for four sites with available data)



Tables

Table 1. Comparison of ice-free CO_2 flux at temporal (i.e. annual, seasonal, diurnal and nocturnal) scales derived from high-frequency eddy covariance measurements over lakes and reservoirs. One standard deviation of the mean represents uncertainty of sub-annual CO_2 fluxes. The numbers in brackets represent the number of observations integrated at a given time scale.

Lake ID	Name	Year	Air-water CO2 fluxes			
			Annual Totals [gC m-2 yr-1]	**Seasonal daily mean [mgC m-2 d-1]**	**Daytime flux [mgC m-2 hr-1]**	**Nighttime flux [mgC m-2 hr-1]**
CA-Dar	Daring Lake	2006	13.6 (n=153)	89±157 (n=95)	0.8±10.7 (n=1685)	12.2±7.5 (n=497)
CA-Est	Eastmain Reservoir	2008	124.4 (n=214)	581±398 (n=214)	22.4±27.5 (n=2790)	26.2±23.4 (n=2117)
		2009	130.4 (n=214)	610±433 (n=214)	21.9±24.2 (n=2786)	30.1±25.1 (n=2127)
		2011	92.3 (n=214)	431±335 (n=214)	18±20.8 (n=2804)	17.9±19.5 (n=2108)
		2012	78.6 (n=214)	367±272 (n=173)	15.2±18.8 (n=2399)	15.7±15.7 (n=1568)
DE-Zrk	Zarnekow Polder Reservoir	2013	17.3 (n=214)	81± 880 (n=170)	-78.6±111.6 (n=2240)	103.1±47.5 (n=1678)
		2014	-53.6 (n=214)	-250± 835 (n=214)	-86±104.1 (n=2817)	81.4±42 (n=2098)
		2015	84.7 (n=214)	396±1148 (n=214)	-41.2±101.2 (n=2791)	84.2±54.6 (n=2139)
FI-Kui	Kuivajarvi Lake	2010	137.6 (n=214)	643±140 (n= 58)	22.8±13.9 (n= 670)	30.2±13.8 (n= 656)
		2011	224.0 (n=214)	1047±304 (n=153)	39.7±17.1 (n=2075)	48.3±21.2 (n=1455)
		2012	164.7 (n=241)	684±274 (n=169)	24.4±16.5 (n=1981)	32.4±18.4 (n=1893)
FI-Pal	Pallasjärvi Lake	2013	52.6 (n=173)	304±154 (n=93)	8.8±9.8 (n=1201)	17.2±9.9 (n=939)
FI-VKa	Valkea-Kotinen Lake	2003	113.6 (n=209)	544±155 (n=208)	22±7 (n=2385)	23.4± 8.8 (n=1848)
		2004	107.5 (n=239)	450±261 (n=238)	16.5±16.4 (n=2986)	21±13.6 (n=2464)
		2005	87.1 (n=227)	384±215 (n=226)	11.4±15.3 (n=2940)	22.6±9.1 (n=2103)
		2006	119.9 (n=254)	472±263 (n=253)	15.8± 13 (n=2983)	23.4±13.4 (n=2824)
		2007	119.6 (n=222)	539±232 (n=221)	20.8±11.3 (n=3033)	24.5±13.5 (n=2038)
FI-Van	Vänajavesi Lake	2016	108.2 (n=237)	457±334 (n=237)	17.6±18.7 (n=2943)	20.8±17.8 (n=2505)
LA-NT2	NamTheun 2 Reservoir	2009	na	1762±186 (n=10)	61±17.8 (n=125)	87±39.2 (n=106)
		2010	na	1623±345 (n=15)	73.5±28.2 (n=146)	63.2±29.7 (n=200)
		2011	na	861±183 (n= 4)	36±16.3 (n= 47)	35.3±13.5 (n= 46)

SE-Mer	Merasjärvi Lake	2005	23.9 (n=165)	145±149 (n=117)	4.7±9.4 (n=1877)	8.6±9.3 (n=835)
SE-Tam	Tamnaren Lake	2010 2011 2012	40.8 (n=216) 35.9 (n=291) 82.7 (n=214)	189±125 (n= 49) 124±161 (n=290) 386±176 (n=105)	6.9± 9.9 (n= 493) 4.9±11.2 (n=3619) 10.8±12.3 (n=1663)	8.6±11.4 (n= 628) 5.3±10 (n=3027) 27.4±16.2 (n= 743)
US-UM3	Douglas Lake	2013 2014	118.7 (n=275) 113.4 (n=275)	432±318 (n=102) 412±313 (n=142)	10.5±25.9 (n=1374) 9.6±24.9 (n=1889)	28.5± 39 (n= 965) 27.7±38.7 (n=1380)
US-RBa	Ross Barnett Reservoir	2007	59.0 (n=365)	162±308 (n=129)	5±23.5 (n=1324)	8.4±27.4 (n=1659)
US-Too	Toolik Lake	2012	46.0 (n=153)	304±130 (n=62)	8±13 (n=1120)	28±27.5 (n=308)