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\textsubscript{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\textsubscript{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\textsubscript{2} flux at all sites. Diel variation converted sites to daily net sinks of CO\textsubscript{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\textsubscript{2} emissions from lakes and reservoirs, revisions in CO\textsubscript{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\textsubscript{2} fluxes in response to natural and anthropogenic drivers.
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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., 2018).
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 CO₂ 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 CO₂ 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 CO₂ flux variability missed by infrequent sampling that may lead to biases in estimates of annual CO₂ flux from lakes and reservoirs.

2. Materials and Methods

2.1 Study sites

Data on air-water CO₂ 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 CO₂ 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 CO₂ 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. ΔpCO₂ (ΔpCO₂_{water} - ΔpCO₂_{air}), 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 CO₂ 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 CO₂ 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 CO₂ fluxes, though with some common elements (Fig. 1). The mean daily CO₂ 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 CO₂ 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 CO₂ fluxes from lakes and reservoirs

Averaged diel CO₂ 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 CO₂ flux dip, the flux decrease was large enough to convert our sites to daily net sinks of CO₂ in only 11% of site-months (Fig. 2a, Table 1). The mean uncertainty of diel CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ fluxes, both sub-monthly and sub-annual modes of variability accounted for two thirds of the site-level daily CO₂ flux variability (range 10-190%). Mean and median uncertainty were 167% and 67% of mean daily CO₂ 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 ($\Delta$T) 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 CO$_2$ 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-Pineda 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
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 CO₂ 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 CO₂ emissions were in the upper end reported for lakes and reservoirs (Table S2). All systems were sources of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ outgassed through freshwaters (Drake et al.,
291 2018; McDonald et al., 2013), providing a possible pathway to constrain freshwater interannual
292 variability. Neglecting this variation is an additional source of bias in our current view on global
293 CO₂ emissions from lakes and reservoirs (Fig. 4).
294
295 Given that EC CO₂ fluxes are affected at both sides of the air-water interface (Wanninkhof et al.,
296 2009), a better constraint of the contribution of lakes to the global carbon cycle will also require
297 reporting and synthesis of additional continuous waterside data (e.g. temperature, dissolved CO₂
298 and O₂), site-level ecosystem characteristics (e.g. nutrient-color legacies, ecosystem metabolism,
299 and aquatic vegetation such as algae) and sampling an increased site diversity within climatic
300 zones (Lehner and Döll, 2004). With more frequent air and aquatic observations, we will better
301 constrain CO₂ fluxes at different time scales, assess the prevalence of temporal patterns in CO₂
302 fluxes, and reduce uncertainty in eddy flux measurements over freshwaters (e.g., Ejarque et al.,
303 2021). Such work will be needed to quantify and evaluate landscape (Buffam et al., 2011; Zwart
304 et al., 2018) to global (DelSontro et al., 2018) carbon budget components from lakes and
305 reservoirs.

5. Conclusions

306 Across 13 study sites with EC flux observations, on average all lakes and reservoirs were net
307 annual sources of CO₂ to the atmosphere. However, the time series unraveled large diel to (sub)-
308 monthly oscillatory CO₂ patterns across sites, among a broad range of biogeochemical and
309 physical site characteristics. These modes of variability accounted for two thirds of daily and a
310 quarter of annual CO₂ flux variation, with sub-annual variability dominating over diel and inter-
311 annual flux variabilities. After integrating these modes of variability into time-resolved fluxes,
312 the CO₂ flux estimates were at the upper end of published CO₂ emissions for lakes and
313 reservoirs. Our results support the idea that long-term, continuous, sub-weekly or sub-daily
314 measurements of carbon dynamics in freshwater aquatic systems are necessary to detect long-
315 term trends of lake carbon fluxes. Long-term, frequent measurements of lake fluxes are also
316 needed to attribute natural and anthropogenic drivers to ecosystem changes that influence the
317 global carbon cycle and its future projections. We advocate for establishing and maintaining a
318 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 CO₂ 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 CO₂ uptake. Note separate flux scale for two reservoirs. Lines represent 10-day moving averages.
Fig. 4 Relationships of the mean daily CO\textsubscript{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 (r\textsuperscript{2}) 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\textsubscript{sat}-e\textsubscript{a}), photosynthetic active radiation (PAR), and pCO\textsubscript{2} air-water gradient (for four sites with available data).
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.

<table>
<thead>
<tr>
<th>Lake ID</th>
<th>Name</th>
<th>Year</th>
<th>Air-water CO2 fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Annual Totals [gC m$^{-2}$ yr$^{-1}$]</td>
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<tr>
<td>CA-Dar</td>
<td>Daring Lake</td>
<td>2006</td>
<td>13.6 (n=153)</td>
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<td>CA-Est</td>
<td>Eastmain Reservoir</td>
<td>2008</td>
<td>124.4 (n=214)</td>
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<td></td>
<td></td>
<td>2009</td>
<td>130.4 (n=214)</td>
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<tr>
<td></td>
<td></td>
<td>2011</td>
<td>92.3 (n=214)</td>
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<tr>
<td></td>
<td></td>
<td>2012</td>
<td>78.6 (n=214)</td>
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<td>Zarnekow Polder Reservoir</td>
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<td>17.3 (n=214)</td>
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<td></td>
<td></td>
<td>2014</td>
<td>-53.6 (n=214)</td>
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<tr>
<td></td>
<td></td>
<td>2015</td>
<td>84.7 (n=214)</td>
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<td></td>
<td>2011</td>
<td>224.0 (n=214)</td>
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<td></td>
<td></td>
<td>2012</td>
<td>164.7 (n=241)</td>
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<td></td>
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<td>US-Too</td>
<td>Toolik Lake</td>
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<td>46.0 (153)</td>
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Supplemental Material

S1. Supplemental Methods Text

Accounting for ice-cover

Current observations of CO₂ fluxes over lakes are mostly limited to an open water season due to wintertime measurement challenges and lack of consistent observations for all sites during ice-covered season. These measurement challenges lead to a persistent under-sampling of ice-covered seasons and periods around ice-on/ice-off. Transitions to/from open-water are often accompanied with large CO₂ efflux (Anderson et al., 1999) and in some cases, comprise a significant proportion of annual CO₂ budget (Denfeld et al., 2018). Therefore, the annual CO₂ flux estimates in Table 1 are conservative.

When the observational CO₂ data extended beyond the predicted ice-free season, the length of ice-free days was adjusted to the first and/or last day of flux measurements. When the observational fluxes were missing data near ice-on/ice-off dates, the seasonal mean daily CO₂ flux for a given lake was imputed to derive annual open water emissions. We assumed negligible CO₂ transfer at the air-lake interface during the ice-covered season.

Footprint screening

Six out of 13 flux towers were placed on the lakeshore, shoals or islands (Table S1) to avoid problems with power supply, wave and ice exposure, or because of the original research question studied (e.g. CO₂ flux in heterogeneous landscape). This introduced an additional problem with CO₂ advection from catchments and flux contamination. While well-selected tower locations minimize the advection term to <3% of CO₂ flux (Morin et al., 2018), the towers located in the middle of the lake can also be affected by CO₂ advection, particularly small lakes surrounded by forest (Esters et al., 2021; Kenny et al., 2017). The contribution of advected air to annual CO₂ lake budgets in this project is unknown and might be substantial. Tower height also influences footprint area and likelihood of encountering secondary circulations (Kenney et al., 2017). To
account for these at some level, data from sites and time periods with suspected significant contribution of mixed footprint were removed from this analysis. PI applied wind directional screening is also applied to avoid land contributions and noted in Table S1.

Gap-filling of missing observations

Observations gap-filled were the climatic (i.e. air temperature, incoming solar radiation, photosynthetically active radiation, horizontal wind speed, friction velocity, relative humidity, barometric pressure, net radiation, vapor pressure deficit) and the lake fluxes (i.e. sensible, latent, and CO₂ turbulent flux), and the in-water (i.e. surface water temperature, CO₂ concentration) variables. However, there is no consistent method of flux gap-filling existing for freshwater waterbodies. Here, we tested two approaches to gap-filling, the artificial neural network (ANN) (Morin et al., 2014) and marginal distribution sampling (MDS) (Wutzler et al., 2018). The MDS approach resulted in a smaller number of end-gaps, always used the same variables for gap-fill and was computationally efficient relative to the ANN approach. Since a standardized gap-filling protocol significantly reduces the uncertainty of compared NEE sums in multi-site syntheses (Moffat et al., 2007), we therefore used the MDS approach for computing filled fluxes and biophysical variables.

Uncertainty analysis

To reflect uncertainty, we calculated the standard error of the mean (i.e. square root of summed variances normalized by square root of number of observations, SEM) for daytime and nighttime half-hourly averages (Table S1). SEM for daytime observations varied from 0.196 μmol m⁻² s⁻¹ in FI-VKa to 1.82 μmol m⁻² s⁻¹ in DE-Zrk, whereas SEM for nighttime observations ranged from 0.200 μmol m⁻² s⁻¹ in FI-VKa to 1.38 μmol m⁻² s⁻¹ in US-UM3. The average nighttime CO₂ uncertainty was higher than daytime uncertainty in seven lakes.

The open-path (OP) gas analyzer measurements were on average one third more uncertain than the closed-path (CP) measurements (Table S1). The daytime SEM in OP ranged from 0.228 μmol m⁻² s⁻¹ to 0.932 μmol m⁻² s⁻¹ (mean: 0.565 μmol m⁻² s⁻¹), while the daytime SEM in CP ranged from 0.196 μmol m⁻² s⁻¹ to 0.558 μmol m⁻² s⁻¹ (mean: 0.382 μmol m⁻² s⁻¹). The CO₂ flux uncertainty in DE-Zrk measured with CP was higher (mean: 1.76 μmol m⁻² s⁻¹) compared to
uncertainties in lakes because a large proportion of emergent macrophytes within the flux tower footprint contributed to much stronger signal and flux magnitudes comparable to wetlands.

CO$_2$ fluxes over freshwater systems are small relative to fluxes to terrestrial systems, show low signal-to-noise ratio, and require the Webb-Pearson-Leuning (Webb et al., 1980) and Burba corrections (Burba et al., 2008) for covarying fluctuations of water vapor flux and temperature. The corrections terms, especially for OP measurements, can be larger than measured CO$_2$ quantities, leading to biased CO$_2$ flux especially when carbon flux is small and corresponding heat flux is large (Helbig et al., 2016) and result in physiologically unreasonable net CO$_2$ flux, such as nighttime uptake in eutrophic water bodies (Lee et al., 2014; Potes et al, 2017). The sites consistently showing such a nighttime uptake were excluded from this meta-analysis.

Intercomparison with other methods

We assume with sufficient sampling period, the continuous EC flux measurements are representative for ecosystems with similar biotic and abiotic conditions. The inter-comparison with other methods of estimating CO$_2$ flux from lakes (i.e. floating chambers, surface renewal model, and boundary layer models) showed varying degrees of agreement. Relative to CO$_2$ flux estimates, the simultaneous measurements with other methods typically agreed within 20%, though periods with large departures up to 2-3 times larger or smaller do occur (e.g., Anderson et al., 1999; Baldocchi et al., 2020; Eugster et al., 2003; Erkkilä et al., 2018; Jonsson et al., 2008; Podgrasjek et al., 2014; Vesala et al., 2006). The agreement varied on level of stratification, overlap in timing of measurements, season, and the selection of piston velocity models. There is good reason to believe that flux tower approaches can be a viable method for estimating lake/reservoir CO$_2$ fluxes, though studies that found greater discrepancies among independent methods and models require reconciliation.

Interannual variability calculation

One standard deviation of annual CO$_2$ fluxes was calculated to determine the inter-annual variation (IAV) of fluxes for sites with multi-year measurements. We acknowledge that calculating the standard deviation from a limited number of site-years (i.e. <5 years) can lead to uncertain estimates of IAV, however, it cannot be further constrained with this study dataset.
With more multi-year time series of continuous measurements, we will be able to determine the 5-year time threshold is sufficient to capture inter-annual CO$_2$ flux variability in freshwater ecosystems.

Regression analysis

We tested several models (e.g. quadratic, linear, exponential, gaussian, etc) available in the library of models in the Curve Fitting Toolbox in MATLAB with the variable number of models’ parameters to select the most robust model. We selected the robust linear least-squares second-order polynomial model with bisquare weighting method. This statistical model maximized the goodness-of-fit (e.g. r$^2$ and rmse), required less parameters to estimate and dealt with nonlinearities. To avoid influences of outliers on fitted curves, values beyond 1$^{st}$ and 99$^{th}$ percentile of each variable were removed before curve fitting.

Fluxes over a macrophyte reservoir (DE-Zrk)

A significant fraction of emergent macrophytes within a flux tower footprint of a shallow reservoir DE-Zrk increased the flux temporal dynamics by an order of magnitude relative to fluxes measured over open water lake surfaces (Table S2). Since the emergent macrophyte stands are common in shallow lakes and reservoirs, the unique CO$_2$ flux over such systems is worth describing separately.

The mean and standard deviation of daily CO$_2$ were 0.072±0.970 µmol m$^{-2}$ s$^{-1}$ (range: -0.858-1.352 µmol m$^{-2}$ s$^{-1}$, Fig. 1, Table 1). Daytime to nighttime hourly fluxes were on average 250% lower, indicating a strong mid-day photosynthetic CO$_2$ fixation of macrophytes, roughly seven times higher than daytime CO$_2$ drawdown observed in open-water systems (Fig. 2). The negative correlation with PAR additionally confirmed a strong control of macrophyte photosynthetic activity over sub-daily CO$_2$ flux variation (Fig. 3). The maximum uptake of the monthly-averaged daily flux amplitudes typically occurred in July ranging 6.15-8.31 µM m$^{-2}$ s$^{-1}$ and declined towards both ends of the ice-free season. At annual timescale, CO$_2$ fluxes indicated a net source of C in two lake-years (Table 1). The mean interannual variability (IAV) of annual CO$_2$ flux 428%. Overall, the mean and median uncertainty of daily CO$_2$ flux were 162% and 421% for DE-Zrk (Fig. 3b). The flux values were several-fold underestimated relative to the
published CO₂ flux estimates for this site (Franz et al., 2016) The CO₂ fluxes contributing to the
tower footprint of DE-Zrk were distinct between the open water and the emergent vegetation
categories. The lack of footprint heterogeneity was not considered in the uniform method of flux
computation applied in this study but was the most significant source of discrepancies in
estimated fluxes between these two studies.
S2. Supplemental references


**S3. Supplemental Tables**

**Supplemental Table S1.** Additional site characteristics of the eddy flux tower sites synthesized in this study.

**Supplemental Table S2.** Summary statistics of the literature-compiled mean daily, annual and inter-annual CO$_2$ fluxes derived from at least four samples per year. Within-study flux variation is expressed as one standard deviation of the (published or calculated) mean. Numbers in brackets indicate the minimum and maximum flux values at given time scale.
### Table S1: Additional site characteristics of the eddy flux tower sites synthesized in this study.

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1 Waterbody type: L-lake; R-reservoir
2 Climatic zone based on Watcha-Gair climate classification map (Sern ec) following Kokko et al., 2009 as analyzed by Rudolf et al., 2017: Db - warm climate, humid; Sfb - warm climate, dry, cool summer; Dib - warm climate, humid; warm summer; Cfa - warm temperate climate, humid; hot summer; Csa - warm temperate climate, humid; hot summer.
3 Submerged/foating (F) and emergent (E) macrophytes: C - Ceratophyllum demersum (SF), Es - Elodea spp., Ew - Lemnaceae SF, M - Myriophyllum spicatum (SF), Pa - Polygonum amphibium (SF), P - Phragmites australis (E), Pd - Phragmites australis (E), T - Typha latifolia (E).
4 Trophic status classification: 0T - oligotrophic (TP<0.5 µg L⁻¹), MT - mesotrophic (TP=0.5 -10 µg L⁻¹), ET - eutrophic (TP>10 µg L⁻¹).
5 Biotic status classification: 0B - oligohaline (DO<7 mg L⁻¹), MB - mesohaline (DO=7-11 mg L⁻¹), PB - polyhaline (DO>11 mg L⁻¹)
6 Depth classification: S - shallow (mean depth ≤3m); D - deep (mean depth>3m)
7 Mean annual air temperature classification: Sm - cold monomictic; Ph - polyhaline; WM - warm monomictic; ES - strongly stratified; SS - warm summer stratification; ED - episodically cold monomictic; EM - episodically warm monomictic; Sp - strongly stratified
8 Sensor type: OP - open path gas and heat; CP - closed path gas and heat.
### Supplemental Table S2: Summary statistics of the literature-compilied mean daily, annual and inter-annual CO2 fluxes derived from at least four samples per year.

Within-study flux variation is expressed as one standard deviation of the (published or calculated) mean. Numbers in brackets indicate the minimum and maximum flux values at given time scale.

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<th>Source</th>
<th>Daily CO2 flux</th>
<th>mgC m⁻² d⁻¹</th>
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<td>31 (18-53)</td>
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<td>Del Sontro et al., 2018</td>
<td>95±49 (1-120)</td>
<td>54±22 (11-120)</td>
<td>na</td>
<td>Continuous</td>
<td>Mass-balance model, temperate</td>
<td>na</td>
<td></td>
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<tr>
<td>Demarty et al., 2011</td>
<td>20±24 (2-49)</td>
<td>19±24 (2-49)</td>
<td>na</td>
<td>Daily</td>
<td>2 lakes, year-round integration, Mass-Balance model, temperate</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>Strauss &amp; McIntyre, 1998</td>
<td>49±47 (1-96)</td>
<td>21-25 yr</td>
<td>na</td>
<td>2 lakes, ice and ice-free season, Mar-Aug sampling, temperate</td>
<td>na</td>
<td></td>
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</tbody>
</table>

### Notes
- **Daily CO2 flux:** Daily time steps
- **Annual CO2 flux:** Daily time steps
- **Inter-annual CO2 flux:** Daily time steps
- **Measurement Frequent:** Year-round integration, Mass-Balance model, temperate
- **Notes:** Year-round continuous; Four lakes; ice-free season; Boreal; boreal; Southern Hemisphere; autumn-1 (5,118 lakes), unspecified lakes sampled yearly; weekly (17 lakes); variable; daily; Multi-year 4 year-1 (1 reservoir) 4 year-1 (other); Space-resolved 89-129 year-1 (daily flux) 15 year-1 (annual flux); Reservoirs, Global summary statistics; Ice-free season, Summer sampling; US Mid-west region; Ice-free season; Subarctic; L. Valkea-Kotinen; Ice-free season; Boreal; Kuivajarvi; Ice-free season; Boreal; L. Gäddtjärn and headwater lakes, Ice-free season; Jun-Nov sample; Boreal; Priest Pot; Ice-free season; May-Oct sampling; Mediterranean; 1 reservoir; ice-free season, boreal; Five lakes; ice-free season, boreal; Eddy covariance; Nine lakes and three reservoirs, ice-free season, boreal; Ice-free with a brief under-ice period; May-Oct sampling, boreal; Five lakes; ice-free season, boreal; Mediterranean; Five lakes; ice-free season, boreal; Global; Six lakes; annual; Apr-Nov sampling; Temperate; Six lakes; annual; Eddy covariance; Global; Chip in peatland; ice-free season; boreal; Two reservoirs; ice-free season, boreal; Eddy covariance; Global; Eight reservoirs; ice-free season, boreal; Eddy covariance; Global; Ten lakes; ice-free season, boreal; Eddy covariance; Global; Six lakes; ice-free season, boreal; Eddy covariance; Global; Seven lakes; ice-free season, boreal; Global; Four lakes; ice-free season, boreal; Eddy covariance; Global; Eight lakes; ice-free season, boreal; Eddy covariance; Global; Ten lakes; ice-free season, boreal; Eddy covariance; Global; Six lakes; ice-free season, boreal; Global; Ten reservoirs; multi-year; ice-free season; temperate; Five lakes; ice-free season, boreal; Eddy covariance; Global; Two reservoirs; annual; ice-free season; boreal; Global; Six lakes; annual; ice-free season; boreal; Global.
**S4. Supplemental Figures**

**Supplemental Fig. S1.** Seasonal patterns of CO$_2$ flux in three example lakes: a) FI-Van - a boreal lake, mesotrophic, mesohumic, deep, fall monomicite with episodic summer mixing due to weak stratification, b) FI-VKa - a boreal lake, mesotrophic, mesohumic, shallow, fall monomicite, strong summer stratification, and c) DE-Zrk – a temperate eutrophic reservoir, shallow, cold polymictic with emergent macrophytes.