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SPECIAL ISSUE-LETTER

Carbon sink and source dynamics of a eutrophic deep lake using multiple flux observations over multiple years

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Scientific Significance Statement

Lakes are hotspots of carbon cycling compared to the surrounding landscape, and depending on a variety of factors and the timescale of interest, lakes can act as both a source and sink of carbon from the atmosphere. Although the importance of growing-season length on annual lake carbon balance is known to be important, short-term processes, such as the brief pulses of carbon from the turnover of ecological communities throughout the year, are not well quantified. Our study documents the annual sum of carbon from a eutrophic lake in an agriculturally dominated watershed depends on climate and the timing of spring and fall turnover. Our results provide evidence for the importance of finer-scale processes in determining annual carbon contributions of lakes.

Abstract

Recent research has shown lakes play an outsized role in carbon cycling, but long-term continuous observations and analysis of carbon dynamics are rare, limiting our understanding of interannual variation, important timescales of variability, and drivers of efflux. Therefore, we examined lake-atmosphere carbon fluxes with the goal of quantifying annual trends and patterns in lake carbon efflux and identifying important timescales. To do so, this study integrated 6 yr of eddy-covariance flux tower observations of lake-atmosphere fluxes with high-frequency observations of in-lake temperature, dissolved oxygen, and partial pressure of CO_2, for a eutrophic lake in Wisconsin, U.S.A. While growing season fluxes are variable and switch between source and sink, annual net carbon fluxes show the lake acts as an annual sink of carbon, with the magnitude depending on climate, along with the timing and strength of fall turnover, with half of the total annual carbon uptake happening in October and November.

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Author Contribution Statement: DER and ARD came up with research question, ARD led deployment of field sensors, all authors assisted with analysis. DER wrote first draft of manuscript with all authors contributing manuscript edits.

Data Availability Statement: All flux tower and buoy meteorological and chemical data and lake metadata are cataloged for public access in the Environmental Data Initiative (EDI) and archived in the North Temperate Lakes (NTL) LTER data repository. Flux tower data including eddy fluxes of carbon and water flux and meteorological data of wind velocity, temperature, humidity, pressure, and radiation are archived at https://portal.lternet.edu/nis/mapbrowse?packageid=knb-lter-ntl.347.1 (Desai 2017, DOI: 10.6073/pasta/babcc869806031bf5d27f7f59579baa0). Buoy-based observations of wind velocity, air, and water temperature profiles, carbon dioxide and dissolved oxygen concentration are archived at: https://portal.lternet.edu/nis/mapbrowse?packageid=knb-lter-ntl.129.18 (Stanley et al. 2017, DOI: 10.6073/pasta/925c177e9cbc0035dd5f97dbc8b5947d). Additional flux tower metadata can be acquired at the Ameriflux site database (http://ameriflux.lbl.gov/sites/siteinfo/US-Men).

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Increasing air temperatures associated with climate change are warming the surface waters of lakes globally (Schneider and Hook 2010; Schmid et al. 2014; O'Reilly et al. 2015). Owing to differences in lake characteristics, this rate of warming is highly variable among lakes (Schmid et al. 2014). The physical factors that both drive and result from this warming include shorter ice cover duration, longer periods of water column stratification, and shifts in hydrology though changes to precipitation. Cascading biogeochemical effects include, but are not limited to, changing water column pH, longer periods of anoxia (Snortheim et al. 2017), and an increase in cyanobacteria (Kosten et al. 2012). Together, the impacts from climate change are expected to alter the net carbon balance of lakes (Alin and Johnson 2007).

Lakes are hotspots of carbon cycling and fluxes compared to the surrounding landscape (Algesten et al. 2004). Aside from being a destination of carbon from surrounding terrestrial ecosystems and part of a hydrological conduit that moves carbon downstream, lakes process significant amounts of carbon internally (Schiff et al. 1990). This processed carbon can end up lower in the watershed, stored in lake sediments, or as increasingly noted in literature, be outgassed to the atmosphere (Raymond et al. 2013). Depending on physical, chemical, and biological processes, lakes can act as both as source and sink of carbon from the atmosphere across different periods of time (Shao et al. 2015). When considering annual lake carbon balance, the overall length of the growing season is known to be an important factor (Alin and Johnson 2007), but carbon balance is impacted by processes at shorter timescales, such as lake metabolism (Staehr and Sand-Jensen 2007).

High-frequency observations, on the order of seconds to hours, are possible for some lake water-column variables such as temperature and dissolved oxygen (DO) and meteorological variables such as air temperature or solar radiation (Staehr and Sand-Jensen 2007). However, similar high-frequency observations of lake-atmosphere CO_2 fluxes are both lacking and methodically challenging (Vesala et al. 2012). High-frequency in situ data collected from lake buoys in north-temperate and polar lakes are typically limited to the summer months due to harsh winter ice conditions, and therefore data collection during the shoulder-seasons, which would capture spring stratification and fall turnover, are rare. This leads to missing fluxes directly preceding and succeeding ice coverage, as well as short pulse efflux events, which propagates significant uncertainties in the estimation of annual net fluxes (Lasslop et al. 2010). Shoreline eddy covariance towers allow continuous observations of lake surface fluxes, but complex patterns of atmospheric turbulent flow and contamination of shoreline fetch or footprint by surface fluxes in the surrounding landscape makes representative and complete temporal coverages of lakes an ongoing challenge (Morin et al. 2017).

The limitations presented by both in situ lake observations and eddy flux measurements may be overcome by using both techniques in tandem to understand to the role of climate drivers and physical lake characteristics on the carbon source or sink behavior of lakes over multiple timescales. Here, observations from the eutrophic Lake Mendota in southern Wisconsin, U.S.A., as part of the Northern Temperate Lakes Long Term Ecological Research study, were used to examine the following questions: (1) Using high-frequency data, what are annual trends and patterns in lake carbon efflux? (2) What timescales of efflux are critical and what are potential drives of efflux during those times?

Methods

Study site

Lake Mendota is a large lake (39.61 km^2) located in Madison, Wisconsin, U.S.A. (43.009, 289.405). The drainage area of the lake (604 km^2) is 67% agricultural lands and 22% urban development (2011 US National Land Cover Database). The lake has a maximum depth of 25.3 m and a mean depth of 12.8 m. The mean hydrological residence time is 4 yr. Wind speeds over the study period averaged 4 m s^{-1}. Mendota is eutrophic, with total phosphorus concentrations $\sim$ 110 μg L^{-1}, total nitrogen $\sim$ 860 μg L^{-1}, and dissolved organic carbon $\sim$ 5 mg L^{-1}.

Field flux observations

Eddy covariance sensors that measure wind speed (CSAT3, Campbell Scientific, Logan, Utah, U.S.A.) and carbon dioxide and water vapor concentrations (LI-7500, Li-Cor, Lincoln, Nebraska, U.S.A.) were installed on a rooftop facing Lake Mendota (Madison, Wisconsin, U.S.A.) during the 2011–2012 winter. The building was 10 m tall, with the sensor height to the lake surface being 11.6 m and horizontally 0.95 m toward the lake surface and 0.93 m above the building.

Eddy covariance from the shoreline off a building poses measurement challenges and a high level of data screening (> 80%). Using an eddy flux surface flux footprint model (Kljun et al. 2015), we identify and remove non-lake data in both the 10 Hz and 30 min data. We then apply a 12^{th} order polynomial planar fit rotation to reduce bias caused by vertical advective fluxes and specifically screen out data within 10° orthogonal to the sonic anemometer to account for a clear vertical velocity bias in those wind directions arising from flow distortion by the building. Data were processed and compared well in two separate flux processing algorithms and we report the fluxes computed from the TK3 software (Mauder and Foken 2015) along with the applying their quality control flags for stationarity, integral turbulence, and propagating their estimate of random error (Mauder et al. 2013). Missing data were filled using a marginal distribution sampling method of the REddyProc R package (Reichstein et al. 2005). For estimating cumulative net ecosystem exchange (NEE), we further filled two long gaps during instrument failure in late 2012, early 2013, and in early 2016 using a multiyear ensemble median flux of the half-hourly gap-filled fluxes from years with fluxes available.

The Lake Mendota Buoy was deployed seasonally during the ice-free season and is located above the deepest spot in Lake Mendota (43.0995, −89.4045). The buoy is equipped with a thermistor string that measures water temperature from the surface to 20 m, as well as a D-Opto DO probe (ENVCO Global, Auckland, New Zealand; 1% accuracy) and a Turner C-Sense CO_2 sonde (Turner Designs, San Jose, U.S.A.; 3% accuracy) installed in 2015 at 0.5 m below the surface. A surface anemometer measures wind speeds at 2 m above the lakes surface. The buoy records data every 1 min. Exchange of O_2 (g-C L^{-1} d^{-1}) at the surface of the lake, expressed in carbon units as a 1 : 1 molar ratio with CO_2, was calculated as:

$$O_2\text{flux} = (12/32)\times(-kO_2)\times(\text{DOobs} - \text{DOsat}) \qquad (1)$$

Where DOobs (mg L^{-1}) is the observed dissolved O_2 in the surface of the lake, and DOsat (mg L^{-1} d^{-1}) is the saturation concentration of O_2 at the observed temperature. Exchange of CO_2 (g-C L^{-1} d^{-1}) is calculated as:

$$\text{CO-}_2\text{flux} = 0.012\times K_H\times kCO_2\times(CO_2\text{obs} - CO_2\text{sat}) \qquad (2)$$

Where K_H (mol L^{-1} atm^{-1}) is Henry's constant for CO_2 based on surface-water temperature (Plummer and Busenberg 1982), CO_2obs (μatm) is the observed dissolved CO_2 in the surface of the lake, and CO_2sat (μatm) is the saturation concentration of CO_2 at the observed temperature. The gas exchange coefficient (kO_2 and kCO_2, m d^{-1}) is calculated as:

$$kO_2 = k600\times(\text{Sc}600/600)^{-0.5} \qquad (3)$$

Where Sc600 is the Schmidt number and is computed independently for O_2 and CO_2 based on water temperature (Winslow et al. 2016). k600, the gas transfer velocity, was derived by the method described in Cole and Caraco (1998) using wind speed, and the method described in Vachon and Prairie (2013) using wind speed and lake area. These two methods were chosen because they encapsulate the range in k600 values predicted by a number of gas transfer velocity models (Dugan et al. 2016). Models were implemented using LakeMetabolizer (Winslow et al. 2016). Gas exchange of O_2 and CO_2 were computed at hourly intervals and are presented as daily means.

Defining seasons and gap filling

Using the Wisconsin State Climatology and Mendota Buoy data, ice-on and ice-off dates as well as thermocline depth were used to define winter, spring turn-over, summer, and fall turn-over seasons. Data were temporally gap-filled using REddyProc (Lasslop et al. 2010) using water temperature in place of soil temperature as a gap-filling input in combination with incoming solar radiation, air temperature, and atmospheric vapor pressure deficit. Missing values were filled using similar-condition lookup tables, by increasing in size time windows, which left gaps larger than 3 weeks unfilled. To evaluate the influence of temperature on NEE, we conducted a wavelet coherence analysis using gap-filled fluxes and environmental variables with a Morlet filter in MATLAB.

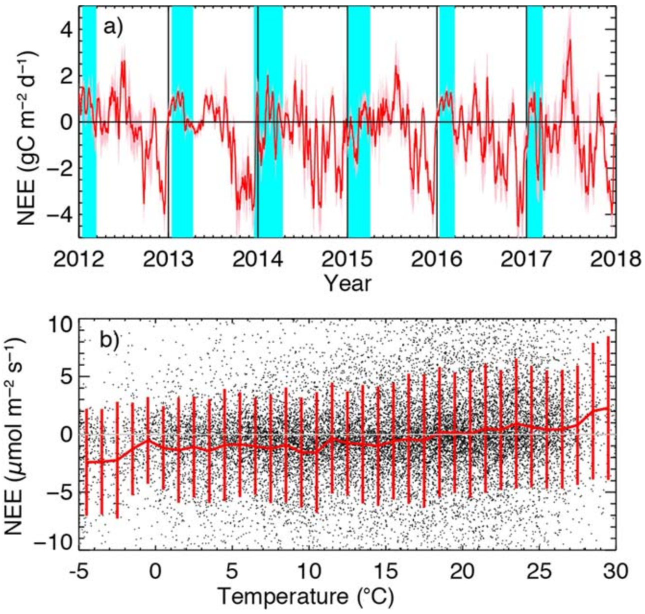

Fig. 1. (**a**) Daily gap-filled NEE of carbon dioxide from 2012 to 2017, blue periods indicating periods of ice overage, with the average non-missing day 71% gap-filled. Positive NEE indicated carbon flux from the lake to the atmosphere. (**b**) Red shows one degree bin averaged NEE and standard deviation.

Results

Annual fluxes

NEE fluxes are shown from 2012 to 2017 in Fig. 1a and binning NEE fluxes by air temperature shows in Fig. 1b increasing net carbon flux to the atmosphere with increasing temperature, most likely due to increased ecosystem respiration. Annual carbon NEE cumulative sums were negative in 2013–2017 and Lake Mendota was a net sink of carbon those years (Fig. 2). Annual cumulative sums of water vapor flux show that the summer season is the most important time period for water vapor fluxes with cumulative sums of water vapor fluxes show that 59.7% of cumulative water vapor flux occurs during May–September while summer and fall together (May–November) contribute 83.9% of water fluxes. Comparatively, annual carbon fluxes are more dynamic, with only 16.0% of cumulative carbon flux occurring during the summer, and a greater contribution of 50.3% during the fall shoulder season. Over the 6 yr, net annual carbon fluxes varied from -55 gC m^{-2} to -232 gC m^{-2}. The smallest year of uptake was 2012, which was roughly one quarter of the largest uptake year of 2014.

There was also interannual variation in season length. The earliest ice-free day in 2012 was on DOY 70, while the latest was DOY 101 in 2014, for a range of 31 d. The time range of first ice-on date was 26 d. Spring turnover lasted on average 23 d, but varied from 17 d (2013) to 28 d (2014), while fall turnover was longer, averaging 71 d, ranging from 53 d (2013) to 96 d (2012).

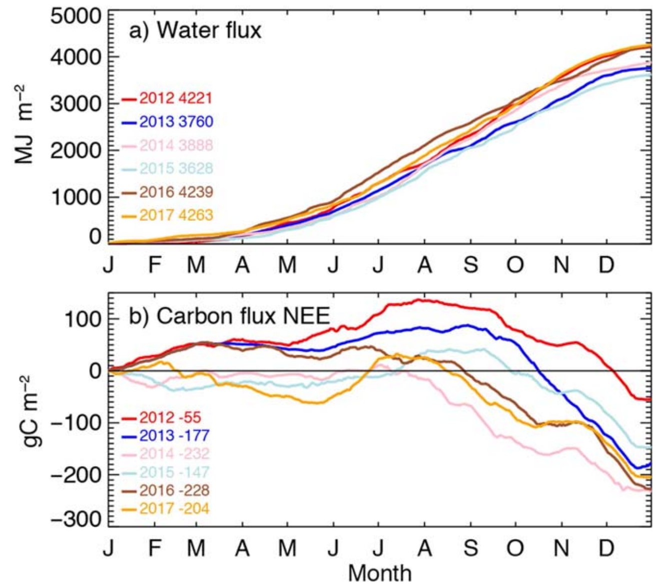

Fig. 2. Cumulative annual Lake Mendota sums of water (**a**) and CO_2 (**b**) flux for 2012–2017 with annual sums noted.

The Lake Mendota buoy was deployed after the onset of spring turnover in all study years, and therefore was unable to capture the uptake of CO_2 seen in the eddy flux data. During the summer months, time series of hourly O_2 gas exchange reveal similar inter-annual variability as eddy flux data (Fig. 3). Based O_2 concentrations, in the late summer and fall of 2012, Lake Mendota was a source of carbon to the atmosphere, whereas it was mainly a carbon sink in 2013. In 2015 and 2016, both O_2 and CO_2 concentrations reveal that Lake Mendota switched from a carbon sink early in the season to a carbon source in late summer. The concentration of CO_2 in Lake Mendota was much less variable than O_2 during the summer of 2015 and 2016. This is likely due to the high pH (8.4) of Lake Mendota, under which the carbonate balance forces CO_2 to dissociate to bicarbonate (Peeters et al. 2016). However, in both years, there was a large CO_2 efflux in late fall as the lake began to turnover, consistent with atmospheric flux observations.

Flux timescales

Times with a high magnitude of coherence between carbon flux and air temperature are shown in Fig. 4. Daily timescales are important, particularly during the summer seasons, but not continuously, implying that at weekly timescales the coherence between flux and temperature breaks down. Yearly timescales reveal high coherence for 2014–

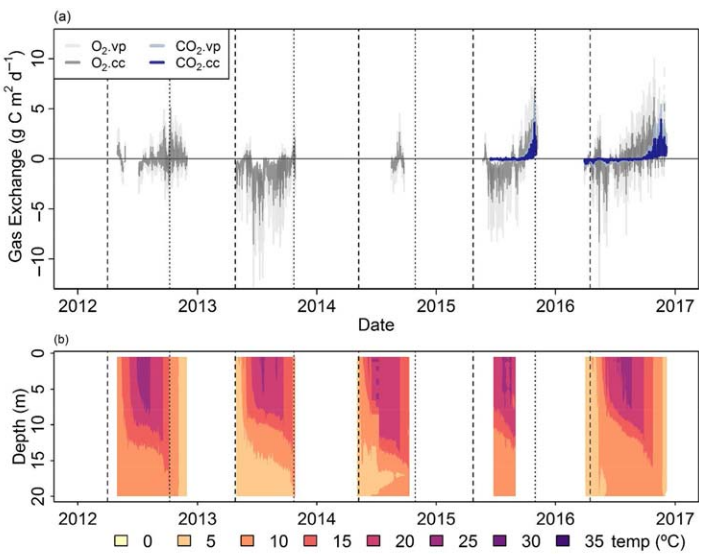

Fig. 3. (**a**) Hourly O_2 and CO_2 gas exchange from the surface of Lake Mendota, measured in situ at 0.5 m beneath the surface in the middle of the lake. Positive values indicate exchange from the lake to the atmosphere. Two models are used to predict gas exchange (vp = Vachon and Prairie 2013, and cc = Cole and Caraco 1998). Dashed lines represent the onset of lake stratification, and dotted lines represent the start of fall turn-over. (**b**) Thermal profile of Lake Mendota from 0 m to 20 m depth.

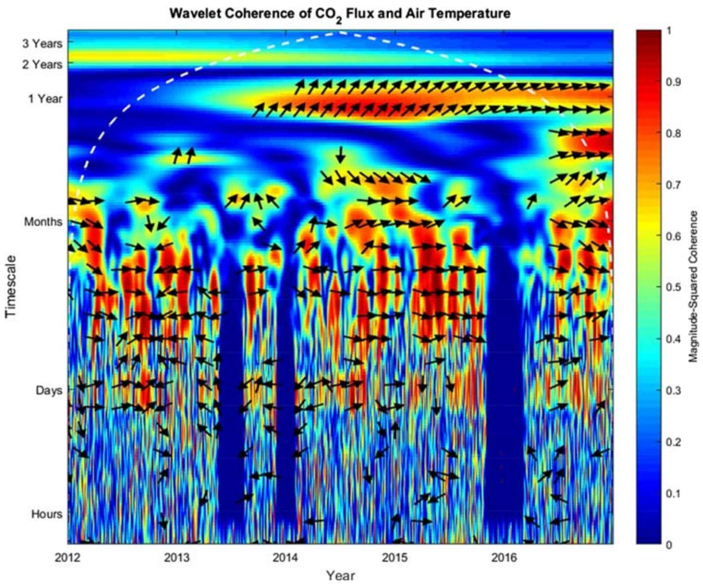

Fig. 4. Morlet wavelet coherence plot of net CO_2 flux and air temperature for 2012–2016 with 1st January of each year labeled. Phase arrows in black represent the time lag between CO_2 flux and air temperature with right facing arrows showing in-phase time series, left facing arrows anti-phase time series, upward facing arrows shows temperature leading flux while a downward facing arrow shows flux leading temperature. Arrows only shown where the coherence is greater than or equal to 0.7. Cone of influence shown in white.

2015, with data gaps likely the cause for the lack of annual coherence throughout the entire study. Over the study period, there are large areas of coherence between daily and monthly timescales, but similar to daily coherence, it is not continuous throughout the year. Most of the flux signal was in-phase with the temperature signal, as shown by right facing arrows where coherence is greater than 70%. Large data gaps are shown here as extended periods with zero coherence.

Discussion

Annual trends and patterns

Carbon fluxes are dynamic and all seasons factor into carbon balance of lakes. Significant cumulative fluxes outside of the summer, stratified period, compared to water fluxes where nearly all of the annual water flux occurs during the warm months of April–November. Seasonally deployed buoys during warm months often miss the shoulder seasons on lakes, and therefore miss critical fluxes that more accurately represent the annual carbon contribution of lakes. On Lake Mendota, small fluxes accumulate over ice covered periods and the direction of fluxes can vary. During turnover, particularly the longer fall turnover, large fluxes were observed and this time period can switch the lake from a summer sink to an annual net source for the year. Most noticeably, at the start of the fall turnover, 2012 was on track to be a net source of carbon and the lake switched to an annual sink during the fall turnover. Similarly, 2013 was a net sink at the end of summer and ended up as an annual source after fall turnover. Lake Erie showed similar switches between source and sink during the summer but is an annual source (Shao et al. 2015). In many cases, eutrophic lakes are reported as carbon sinks, but many of these studies only incorporate summer measurements when the lake is highly productive (Balmer and Downing 2011; Solomon et al. 2013; Dugan et al. 2016) and hence extrapolate to get annual sums, incorporating significant errors. In boreal lakes, the mean residence time was a larger factor, more-so than mean lake temperature, in determining how much carbon inputs are lost to mineralization, sedimentation, or flux to the atmosphere (Algesten et al. 2004). This implies the physical hydrology of lakes, which is less likely to be impacted by climate change, could buffer temperature-induced changes to the carbon cycling. Recent research has shown that eutrophication can cause lakes to switch from being net carbon sources to sinks (Pacheco et al. 2014), showing that the significant role human process can have in lake and global carbon cycling.

Important timescales

Observing carbon fluxes at an annual timescale is critical for understanding the contribution of lakes to the global carbon cycle. However, better understanding sub-annual drivers of carbon cycling will allow us to better predict future changes in lake state as a carbon source or sink. This includes traditional summer sampling, when phytoplankton production and respiration are at their peak (Alin and Johnson 2007), but also winter ecology, which may have a large influence on carbon cycling during ice-breakup (Hampton et al. 2017).

Daily timescales are also important in lakes (Liu et al. 2011; Solomon et al. 2013; Shao et al. 2015; Liu et al. 2016), as solar radiation is the main driver of primary productivity (Harris 1973) and daily water temperature cycles (Bristow and Campbell 1984). In lakes, nighttime CO_2 fluxes, relative to daytime fluxes, are larger and more variable, flipping the expected idea from terrestrial studies that daytime data only is enough to quantify fluxes (Podgrajsek et al. 2016). Results from this work show that daily timescales influence lakes during all seasons, however during summer, periods of coherence can linger beyond daily scales.

Furthermore, there are significant timescales in-between daily and seasonal timescales that are emerging in the literature as being important. Liu et al. (2016) and Liu et al. (2011) show multiday synoptic weather patterns driving physical lake mixing. Increased wind speeds above the lake surface are correlated with increased mixing and lake-atmosphere fluxes. Shao et al. (2015) show a correlation between monthly CO_2 flux and chlorophyll, most likely due to trophic cycles between phytoplankton and zooplankton, similar to the result of Ouyang et al. (2017), which showed lowered fluxes during algal blooms over the period of months. The results of this study highlight the relative strong connection between carbon fluxes and environmental temperature on timescales around 20–30 d, in-between daily and seasonal scales, consistent with previously reported trophic interactions.

Future monitoring of carbon cycling in lakes need to focus on observations that span these timescales. Eddy covariance methods are a good high-frequency option that can pair with other types of data, from remote sensing (Ouyang et al. 2017) to in situ buoy data as presented in this work. Recent work has combined a network of five sensors sites across a single lake (Lee et al. 2014) while another study showed that towers can be located on lakes and still produce usable data (Morin et al. 2017) depending on height and position of sensor (Kenny et al. 2017). Using similar techniques in the water column, aquatic eddy correlation can measure in situ oxygen fluxes (Brand et al. 2008). Not without limitations, eddy covariance methods are a good way to measure lake-atmosphere gas fluxes at timescales not easily matched by other methods.

Conclusion

While challenging, eddy covariance methods allow high-frequency observations of lake carbon fluxes. The temporal variation in carbon flux is high and while daily cycles are a strong signal in the observational record, there are also cycles that exert influence carbon fluxes over periods ranging from several days to several weeks into seasonal timescales. Factors that contribute to these cycles include lake metabolism, mixing, stratification and trophic patterns, as well as climate related factors like length of turnover and growing season. When combined, these cycles act to determine the net carbon balance of a eutrophic deep lake, which varies between being a carbon source and sink on annual timescales.

With climate change projected to increase lake temperatures while decreasing the duration of ice coverage, the relative importance of processes that contribute to annual lake carbon balance are expected to change going into the future. With longer ice-free periods as well as increased strength of algal blooms, the annual carbon sink of lakes could increase. Potential strengthening of stratification events and higher rates of input of carbon into lakes from the landscape could increase the carbon source. Overall, our capacity to predict the net balance of carbon flux to the atmosphere can be expected to show higher amounts of interannual variability. Improvements to lake observational records and modeling will help separate the complex effects of how carbon fluxes respond in the future. How lake carbon fluxes response to future climate and landscape perturbations can have outsized effects on both global carbon fluxes, as lakes are carbon processing hotspots, as well as regional and local carbon-credit policy matters, as lake carbon fluxes can impact regional and local carbon emission reduction plans.

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