Diurnal sampling reveals significant variation in CO$_2$ emission from a tropical productive lake

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Abstract

It is well accepted in the literature that lakes are generally net heterotrophic and supersaturated with CO$_2$ because they receive allochthonous carbon inputs. However, autotrophy and CO$_2$ undersaturation may happen for at least part of the time, especially in productive lakes. Since diurnal scale is particularly important to tropical lakes dynamics, we evaluated diurnal changes in pCO$_2$ and CO$_2$ flux across the air-water interface in a tropical productive lake in southeastern Brazil (Lake Carioca) over two consecutive days. Both pCO$_2$ and CO$_2$ flux were significantly different between day (9:00 to 17:00) and night (21:00 to 5:00) confirming the importance of this scale for CO$_2$ dynamics in tropical lakes. Net heterotrophy and CO$_2$ outgassing from the lake were registered only at night, while significant CO$_2$ emission did not happen during the day. Dissolved oxygen concentration and temperature trends over the diurnal cycle indicated the dependence of CO$_2$ dynamics on lake metabolism (respiration and photosynthesis). This study indicates the importance of considering the diurnal scale when examining CO$_2$ emissions from tropical lakes.

Keywords: pCO$_2$, CO$_2$ flux, diurnal variations, tropical productive lake.

1. Introduction

It is widely accepted that lakes are typically supersaturated with CO$_2$ relative to the overlying atmosphere (Kling et al., 1991; Cole et al., 1994; Duarte and Prairie, 2005). This net heterotrophic condition is believed to predominate as ecosystem respiration frequently exceeds ecosystem primary production in lakes due to the input of allochthonous organic matter from their catchments (Del Giorgio et al., 1999; Pace et al., 2004). However, recent studies have shown that although heterotrophy is frequent it is not a general rule. CO$_2$ undersaturation and/or autotrophy have been recorded in lakes, especially on those with high production rates (e.g. Xing et al., 2005; Gu et al., 2011; Laas et al., 2012). Productive lakes support lower respiration rates than the unproductive ones and then tend to be net CO$_2$ sinks (Duarte and Agusti, 1998). Besides lake productivity, other factors are thought to influence the metabolism and partial pressure of CO$_2$ (pCO$_2$) in the surface waters of lakes, such as temperature, dissolved organic carbon concentration, and dissolved inorganic carbon inputs from the watershed (e.g. Hanson et al.,...
2. Material and Methods

2.1. Site description

Lake Carioca (19°45’26.0"S; 42°37’06.2"W) is located in the Rio Doce State Park (Parque Estadual do Rio Doce, PERD; Figure 1) in an Atlantic Forest remnant in Minas Gerais, Brazil. The park is part of the middle Rio Doce Lacustrine System, which consists of more than two hundred lakes and ponds of varying size, morphometry and trophic state. Roughly 51 lakes are inside PERD, including Lake Carioca, and thus protected from direct human impacts. However, PERD is surrounded by agriculture, pasturelands, and large areas of Eucalyptus spp plantations that have considerable impacts on the lacustrine system and the forest of the park. Carioca is a small (0.14 km²) shallow lake (max. depth = 11.8 m, Bezerra-Neto et al., 2010) and exhibits high production rates (annual average of 497 mgC.m⁻².d⁻¹, PELD Technical Report, unpublished data). It mixes vertically once a year during the dry season (between May and August), when primary production is boosted by nutrients from the hypolimnium of the lake.

2.2. Sampling and calculations

Samples were collected at the end of the dry season (August, 2011) just after the water mixing and at the beginning of thermal stratification. Basic limnological data including water temperature, pH, conductivity and dissolved oxygen (D.O.) were taken at the deepest point of the lake with a Hydrolab DS 5 (Hydromet Inc.) probe at depth intervals of 0.5 m. Water samples for analysis of nutrients and chlorophyll-α determination were collected at 4 depths corresponding to 100%, 10% and 1% of surface irradiance, as well as the aphotic zone (defined with a 1400 series International Light Technologies radiometer). These data are not discussed in detail herein and are provided as background information only.

Surface water CO₂ partial pressure (pCO₂) and CO₂ flux across the air-water interface were measured every 4 hours at the deepest point of Lake Carioca over two diurnal cycles. Direct measurements of pCO₂ were taken by headspace equilibration according to Cole and Caraco (1998) with modification. Three 30 mL glass bottles (triplicates) were filled with 20 mL of lake surface water (0.5 m depth) and immediately capped and sealed with rubber and metal caps. Ten mL of ambient air was introduced to each bottle with a syringe and needle through the rubber cap. The bottles were then shaken vigorously for 60 seconds to allow for equilibration of the air and water phases for CO₂. Headspace air was collected with a syringe and injected in an infrared gas analyser (IRGA) (environmental gas monitor EDSEGM4; PP-Systems, Hitchin, Hertfordshire) for pCO₂ measurement. pCO₂ of ambient air (pCO₂air) was also measured by the IRGA. Surface water CO₂ concentration (Csw) and the saturation concentration of CO₂ (Csat) were calculated from measured pCO₂, and Henry’s constant at ambient temperature (KH) according to Henry’s law (Weiss, 1974) (Equation 1 and 2):

\[ C_{sw} = pCO_2 \times KH \]  
\[ C_{sat} = pCO_2 \times KH \]

CO₂ fluxes across air-water were estimated using the following equation according to Cole and Caraco (1998) (Equation 3):

\[ \text{Flux} = \alpha \times k (C_{sw} - C_{sat}) \]  
where \( \alpha \) is the factor for chemical enhancement of diffusion (Wanninkhof and Knox, 1996) and \( k \) is the coefficient of gas exchange for CO₂ at a given temperature. \( k \) was calculated from \( k_{600} \) for low wind speeds (Equation 4) (Cole and Caraco, 1998) and from Schmidt numbers ratio (Equation 5) (Jähne et al., 1987):

\[ k_{600} = 2.07 + 0.215 \times U_{10}^{-1.7} \]  
\[ k = k_{600} \times (Sc / 600)^{0.657} \]

\( U_{10} \) is wind speed at 10 m and was estimated with the Smith (1985) equation using measured wind speed at 1 m by an anemometer at the centre of the lake. Sc is the in situ Schmidt number for CO₂ (Jähne et al., 1987).
Continuous measurements of dissolved oxygen concentration were taken by an automated sensor (D-Opto Logger, Zebra-Tech Ltd.) deployed in the centre of the lake at 0.5 m depth.

### 2.3. Statistical analysis

*T*-tests were used to check for differences in surface water $pCO_2$ between day and night and to check for differences between surface water $pCO_2$ and $pCO_2$ in the overlying atmosphere. All tests were performed in Statistica 7.0 software.

### 3. Results

Limnological conditions of Lake Carioca in August (2011) are summarised in Table 1. Water temperature ranged from 21.4 °C at the bottom to 23.6 °C at the surface, showing the beginning of thermal stratification. The lake
exhibited a well-developed oxycline at approximately 4 m and an anoxic hypolimnium. The water was alkaline (pH c. 8) down to 4.5 m but pH decreased to c. 6 at the lower layers. The dissolved oxygen and pH profiles indicated high respiration rates and CO₂ concentrations at the bottom of the lake.

Surface water $p\text{CO}_2$ ($p\text{CO}_2_{\text{water}}$) ranged considerably (from 389.7 to 643.3 matm) in Lake Carioca during the sampling period and had a mean value of 488.8 ± 78.6 μatm. Mean night $p\text{CO}_2_{\text{water}}$ (565 matm ± 55.3 (± SD) from 21:00 to 5:00) was significantly higher than mean day $p\text{CO}_2_{\text{water}}$ (436.1 matm ± 25.5 (± SD) from 9:00 to 17:00) ($t$ = –8.14; d.f. = 15; $p < 0.001$, Figure 2), showing significant changes in the CO₂ dynamics of this lake within a day. A strong metabolic control of lake’s CO₂ was evidenced by the similar but opposite trends of dissolved CO₂ and O₂ over the diurnal cycle (Figure 3A). As expected, during daytime photosynthesis lowered water $p\text{CO}_2$ and raised dissolved oxygen (D.O.) concentration. At night, when just respiration occurs, $p\text{CO}_2$ increased considerably and the concentration of D.O. in the water reduced ($p$ < 0.001) but generally showed small differences between CO₂ and O₂ variations suggest that other factors may also have some influence on the lake’s CO₂ concentration.

Table 1. Limnological data at selected depths in Lake Carioca during the dry season (August, 2011).

<table>
<thead>
<tr>
<th>Depth (m) Variables</th>
<th>0</th>
<th>1.5</th>
<th>4.5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water temperature(°C)</td>
<td>23.6</td>
<td>22.8</td>
<td>21.8</td>
<td>21.4</td>
</tr>
<tr>
<td>pH</td>
<td>8.03</td>
<td>8.06</td>
<td>6.32</td>
<td>6.14</td>
</tr>
<tr>
<td>Conductivity ($\mu$S.cm⁻¹)</td>
<td>28</td>
<td>28</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>D.O. (mg L⁻¹)</td>
<td>12.7</td>
<td>12.8</td>
<td>4.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Alk. (meqCO₂.L⁻¹)</td>
<td>0.26</td>
<td>0.24</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>Chlorophyll-a (µg.L⁻¹)</td>
<td>49.2</td>
<td>58.8</td>
<td>105.3</td>
<td>57.7</td>
</tr>
<tr>
<td>Primary Productivity (mgC.m⁻¹.h⁻¹)</td>
<td>10.1</td>
<td>12.0</td>
<td>5.7</td>
<td>0</td>
</tr>
<tr>
<td>PO₄³⁻ (µg.L⁻¹)</td>
<td>2.0</td>
<td>1.5</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>P₅₀ (µg.L⁻¹)</td>
<td>14.6</td>
<td>23.4</td>
<td>16.8</td>
<td>18.4</td>
</tr>
<tr>
<td>NH₄⁺ (µg.L⁻¹)</td>
<td>11.5</td>
<td>9.1</td>
<td>87.4</td>
<td>347.2</td>
</tr>
<tr>
<td>NO₃⁻ (µg.L⁻¹)</td>
<td>0.5</td>
<td>0.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>NO₂⁻ (µg.L⁻¹)</td>
<td>5.2</td>
<td>4.3</td>
<td>3.2</td>
<td>0.3</td>
</tr>
<tr>
<td>N₅₀ (µg.L⁻¹)</td>
<td>873.7</td>
<td>837.6</td>
<td>931.0</td>
<td>724.9</td>
</tr>
<tr>
<td>SiO₄ (mg.L⁻¹)</td>
<td>0.4</td>
<td>0.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

CO₂ emission from Lake Carioca was low, showing a maximum of 2.4 mmolCO₂.m⁻².d⁻¹ at 1:00 of the first day (Figure 5). Mean CO₂ flux throughout the studied period was only 0.9 mmolCO₂.m⁻².d⁻¹ ± 0.8 (± SD). Low values of CO₂ efflux from Lake Carioca are consequences of the relatively low $p\text{CO}_2$ in its water and almost null wind speeds registered during the sampling period.

4. Discussion

Our results bring to light significant diurnal changes in $p\text{CO}_2_{\text{water}}$ and CO₂ emissions from a productive tropical lake. The use of the diurnal approach demonstrated that despite the belief that lakes are generally net heterotrophic and supersaturated with CO₂, Lake Carioca was not a constant source of CO₂ and was heterotrophic only during the night. Diurnal dynamics of CO₂ have been recorded in temperate lakes (e.g. Sellers et al., 1995; Cole and Caraco, 1998; Hanson et al., 2006) but generally showed small
Diurnal CO₂ variation in a tropical lake

Cole and Caraco (1998) for instance, recorded small CO₂ changes within a day in midsummer and even smaller ones during the spring in Mirror Lake. Differently, the significant variation between day and night in CO₂ dynamics recorded for the tropical and productive Lake Carioca-southeast Brazil can be explained by large metabolic differences between periods of the day, which is not pronounced on higher latitude and/or unproductive lakes. As shown here, in productive and warm lakes, gross primary production can be high enough to equilibrate or eventually exceed respiration rates during daytime. Moreover, although this study was conducted only during the dry season, it is likely that diurnal variation in pCO₂ in Lake Carioca is even larger during the rainy season. The higher mean temperature and greater input of nutrients and dissolved organic carbon from the watershed during the rainy season (summer) might favour both autotrophy and heterotrophy in the lake (Brown et al., 2004; Staehr and Sand-Jensen, 2007; Marotta et al., 2012) likely resulting in higher amplitude of diurnal CO₂ variations (Marotta et al., 2010).

Surface water pCO₂ registered in Lake Carioca is very low in comparison to the mean pCO₂ for tropical lakes available in the published literature (1804 matm, Marotta et al., 2009). Also differently from what was found by other studies that covered tropical lakes (e.g. Cole et al., 1994; Marotta et al., 2009), Lake Carioca is a small source of atmospheric carbon in comparison to higher latitude lakes. While CO₂ emissions from Lake Carioca averaged only 0.9 mmolCO₂.m⁻².d⁻¹, other studies have recorded CO₂ effluxes of 20.9 mmolCO₂.m⁻².d⁻¹ from Arctic lakes (Kling et al., 1991), 55.6 mmolCO₂.m⁻².d⁻¹ from a boreal humic lake (Huotari et al., 2009), and 1200 and 90 mmolCO₂.m⁻².d⁻¹ from two clear-water temperate lakes (Riera et al., 1999). The registered low values of pCO₂ and CO₂ efflux from Lake Carioca are probably a consequence of its high autotrophic activity, particularly during the studied period when vertical mixing induces high production rates (640 mgC.m⁻².d⁻¹; PELD Report, 2012) and scarce rainfall limits the input of allochthonous dissolved organic carbon to the lake likely reducing its respiration rates (Cole et al., 2000). Moreover, the lack of rainfall can also lead to lower values of pCO₂ in Lake Carioca in the dry season than in the rainy season since rainfall can enhance CO₂ inputs from groundwater to lakes (Marotta et al., 2010).

As shown in this study, diurnal changes in CO₂ can be significant in tropical waters and ignoring this variation may render misevaluations and misconclusions of the role of tropical aquatic ecosystems in the global carbon cycle. Such conclusions bring new possibilities for further studies concerning the general acceptance of a predominant heterotrophy of lakes, and highlight potential temporal changes between net autotrophy and net heterotrophy in lakes, especially in the tropical and productive ones where temperature and nutrients maintain high autochthonous production rates.
Acknowledgements

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References


Diurnal CO₂ variation in a tropical lake


Erratum

Due to a formatting error in the article “Diurnal sampling reveals significant variation in CO₂ emission from a tropical productive lake” published in volume 74, issue 3 (suppl.), p. 113-119, in the page 116, first column, lines 8, 10 and 12 and in the page 117, second column, line 24 where you read “matm”, you should read “µatm”.

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