Temperature-dependence of the relationship between pCO_2 and dissolved organic carbon in lakes

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Abstract

The relationship between the partial pressure of carbon dioxide (pCO_2) and dissolved organic carbon (DOC) concentration in Brazilian lakes, encompassing 194 lakes across a wide latitudinal range in the tropics, was tested. Unlike the positive relationship reported for lake waters, which was largely based on temperate lakes, we found no significant relationship for warm low-latitude lakes, despite very broad ranges in both pCO_2 and DOC. These results suggest substantial differences in carbon cycling in warm lakes, which must be considered when up scaling limnetic carbon cycling to global scales.

1.Introduction

Lakes cover less than 2% of the continent's surface [Downing et al., 2006; McDonald, 2012], but play a significant role in the global carbon (C) cycle [Cole et al., 1994; 2007; Tranvik et al., 2009], contributing significantly to C burial and emissions to the atmosphere [Cole et al., 2007; Downing et al., 2008 and Tranvik et al., 2009]. Dissolved organic carbon (DOC) represents a major C pool in lakes, with both autochthonous and allochthonous contributions [Xenopoulos et al., 2003; Duarte and Prairie, 2005; Duarte et al., 2005; Sobek et al., 2005; Cole et al., 2007; Prairie 2008; Marotta et al., 2009; Tranvik et al., 2009; Larsen et al., 2012], supporting heterotrophy tactility [Sobek et al., 2007] and affecting key biological and physico-chemical processes involved in C cycling [Steinberg et al., 2006]. Large inputs of terrestrial organic C and its subsequent mineralization have been suggested to be a major driver of CO_2 supersaturation commonly encountered in lakes [Xenopoulos et al., 2003; Duarte and Prairie, 2005; Duarte et al., 2005; Sobek et al., 2005; Cole et al., 2007; Prairie 2008; Marotta et al., 2009; Larsen et al., 2012].

The mechanistic connection between DOC and heterotrophic CO_2 production is believed to underpin the significant positive relationship between pCO_2 and DOC reported in comparative analyses [Houle, 1995; Sobek et al., 2005; Larsen et al., 2012]. However, recent analyses have revealed that the relationship between pCO_2 and DOC in lake waters is regionally variable and not universal [Lapiere and del Giorgio, 2012]. Hence, relationship between pCO_2 and DOC reported in comparative analyses based on data sets dominated by temperate and high-latitude lakes may not be extrapolated for all kinds of lakes, mainly because of the tropical warm lakes are generally underrepresented in global caught [Raymond et al., 2013].

One of priority for comparative study is the latitudinal variance, where lake temperature, ice cover and mixing regime will differ and these climatically driven processes, in turn, should strongly influence OC cycling [Hanson et al., 2015]. At low latitudes, warm conditions over the whole year may impose intrinsically faster rates of C cycling in terrestrial [Ometto e al., 2005] and aquatic [Marotta et al., 2009; Marotta et al., 2010] ecosystems compared to the low rates characteristic of temperate systems in winter. High temperatures affect heterotrophic activity and the associated mineralization rates of organic matter in soils [Davidson et al., 2006], waters [López-Urrutia et al. 2007; Wohlers et al. 2008; Regaudie-de-Gioux and Duarte 2012] and aquatic sediments [Wadham et al., 2012; Gudasz et al., 2010, Marotta et al., 2014]. An enhanced heterotrophic activity in tropical ecosystems would support high fluxes of CO_2, leading to CO_2 enrichment in lake waters through inputs from in flowing waters and mineralization processes in the water column and sediments.

A previous comparative analysis, characterized by a paucity of low latitude data, reported pCO_2 in lake waters to be independent of temperature [Sobek et al., 2005]. However, a positive relationship between temperature and pCO_2 was observed when subtropical and tropical ecosystems were included in the analysis [Davidson et al., 2004; Marotta et al., 2009; Dillon et al., 2010]. Hence, the relationship between lake pCO_2 and DOC could also be temperature-dependent and, therefore, may differ between temperate and tropical lakes. Here, we test the applicability of the relationship between pCO_2 and DOC, largely derived from north-temperate-cold lakes [Houle, 1995; Sobek et al., 2005; Larsen et al., 2012], to tropical and subtropical lakes in Brazil. Brazil has a large territory in the tropics, showing a high density of lakes and ponds [Downing et al., 2006], with a diversity of conditions that render them appropriate to examine general patterns [e.g. Marotta et al., 2009].

2.Methods

2.1.Study area and Lakes

Brazil extends from 5° 16' 20" North to 33° 44' 42" South, showing an area of approximately 8,547,000 km^2 that represents half of South America and encompasses a high diversity of low-latitude landscapes [Ab`Saber, 2003] predominantly located within tropical latitudes. We conducted a survey of pCO_2 and DOC between 2003 and 2011 in surface waters of 166 permanent lakes from 0 to 33° of latitude across Brazil (Figure 1), yielding a total of 225 water samples. The lakes were sampled in representative biomes of Brazil: (1) Amazonia Forest (Amazonia Biome, n = 65), (2) Pantanal Floodplain (Pantanal Biome, n = 29) and the (3) Tropical ($< 24^o$ of latitude) and (4) Subtropical ($> 24^o$ and $< 33^o$ of latitude) Coasts, both in the Atlantic Forest Biome (n = 35 and n = 37 lakes, respectively; Figure 1). These biomes follow the classification of the Brazilian Institute of Geography and Statistics for biomes (IBGE 2004, ftp://geoftp.ibge.gov.br/mapas_tematicos/mapas_murais/biomas). Our data set encompasses a broad inter-lake heterogeneity (n=166) for pCO_2 and DOC simultaneously sampled among Brazilian biomes and along the latitudinal gradient, independent of the year's season.

The Amazonian Forest biome is formed by the most extensive hydrographic network of the globe, the Amazon River basin that occupies a total area about 6.11 million km² from its headwaters in the Peruvian Andes to the mouth in the Atlantic Ocean (ANA – www.ana.gov.br). The Amazon Forest is the Brazilian biome characterized by higher mean annual precipitation (approximately 2200 mm) coupled to warm mean air temperatures around 25°C and high cloud coverage and humidity with low fluctuations over the whole year [Chambers, 1999]. We sampled a wide variety of lakes, characteristic of different areas of the Amazonian Forest, encompassing "clear" (low DOC and suspended solids), "white" (low DOC and high suspended solids) and "dark" (high DOC and low suspended solids) lakes.

The Pantanal Floodplain is the world's largest tropical freshwater wetland, extending across an area of about 150,000 km^2 between 16° and 20° S and 58° and 55° W [Por, 1995]. Annual averages temperature and precipitation are approximately 22 °C and 1,000 mm, respectively [Mariot et al., 2007], with a strong seasonality and subsequent variation in the flooded area [Junk and Nunes da Cunha, 2005]. The high-water period occurs during the rainy summer (usually from September to December), and low waters typically during the dry winter (from March to July) [Hamilton, 2002].

The Atlantic Forest biome extends along a broad latitudinal belt between 5° and 30° S from subtropics to tropics and a narrow longitudinal section between 55° and 56° W, occupying an area of 1.11 million km^2 along the Brazilian coast (IBGE-www.ibge.gov.br). This biome is characterized by numerous shallow coastal lakes receiving high inputs of refractory organic matter [Farjalla et al., 2009] derived from the typical open xerophytic vegetation on sandy soils, where water retention is low [Scarano, 2002]. The mean air temperatures vary from 27° C in winter to 30° C in summer at the tropical coast [< 24° of latitude; Chellappa et al., 2009] and from 17 and 20° C at the subtropical coast [> 24° of latitude; Waechter, 1998]. The mean annual precipitation reaches 1,164 mm [Henriques et al., 1986] and 1,700 mm [Waechter, 1998] in the tropical and subtropical Brazilian coast respectively. This biome is also characterized by strong seasonality, with rainy summers and dry winters [Chellappa et al., 2009].

2.2 Sampling Design and Analytical Methods

Our sampling design encompassed the most representative Brazilian biomes from tropical and subtropical coastal areas to tropical and subtropical forests (Amazon and Atlantic Forest) and inland wetlands (Pantanal), with the intra-lake heterogeneity and seasonal fluctuations randomly assessed and further integrated by means of each ecosystem. We joined 194 lakes, including 166 from our own survey plus 28 from the published literature. The values reported here represented, on an opportunistic manner, daily averages (N= 4 or 5 samples) for a given year season or/and one sampling time over different seasons, which were also both integrated by means of each lake.

pH, salinity and temperature in waters were measured *in situ*. pH was determined using a pH meter (Digimed – DM2) with a precision of 0.01 calibrated with standard solutions of 4.0 and 7.0 units of pH before each sampling hour. Temperature and salinity were measured using a Thermosalinometer (Mettler Toledo - SevenGo SG3) coupled to a probe inLab 737 previously calibrated with 0.01M KCl. Surface lake waters for total alkalinity and DOC analyses were collected taking care to avoid bubbles at about 0.5 m of depth using a 1L Van Dorn bottle. Alkalinity was determined in the field by the Gran´s titration with 0.0125 M HCl immediately after sampling [Stumm and Morgan, 1996]. Water samples for DOC were pre-filtered (0.7mm, Whatman GF/F) and preserved by acidification with H_3PO_4 85% to reach $pH < 2.0$ in sealed glass vials [Spyres et al., 2000]. In the lab, DOC was determined by high-temperature catalytic oxidation using a TOC-5000 Shimadzu Analyzer. pCO_2 concentrations in surface waters were calculated from pH and alkalinity following Weiss [1974], after corrections for temperature, altitude and ionic strength according to Cole et al. [1994].

Aware of the difficulties in determining the pCO_2 in lakes with high contribution of organic compounds [Wang et al., 2013] and also the possible overestimation due to the method of TA and pH rather than direct measurements of pCO_2 [Abril et al., 2015], we tested the relationship of pCO_2 and DOC considering the raw data and after correcting the contribution of organic acids on TA and subsequent pCO_2 data, using the fitted linear regression for the medians and averages values of the relative difference between calculated and measured pCO_2 with ranked pH and DOC values, according the data disposable of Abril et al., [2015] (Figure 3 and 4, more detail in support material).

2.3. Statistical Analyses

The variables pCO_2 and DOC did not meet the assumptions of parametric tests even after logarithmic transformations [Zar, 1996], as data were not normally distributed (Kolmogorov-Smirnov, $p < 0.05$) and variances were heterogeneous (Bartlett, $p > 0.05$). Therefore, we used medians and non-parametric tests to compare these variables among biomes (Kruskall-Wallis followed by Dunn`s multiple comparison post hoc test, $p < 0.05$). The linear regression equations were fitted to compare our results with previous studies from Sobek et al., [2005]. Statistical analyses were performed using the software Graphpad Prism version 4.0 for Macintosh (GraphPad Software, San Diego, CA).

3.Results

The lake waters surveyed were warm across all biomes (median 25-75% interquartile range = 27.5° C, 25.2 – 30.1), but colder in subtropical coastal lakes (23.4° C, 20.0 – 26.2) compared to Pantanal and Amazonian lakes (29.5° C, 27.7 – 31.4 and 29.4° C, 27.6 – 31.0, respectively; Dunn's test, $p < 0.05$, Figure 2a). DOC concentrations were consistently high (6.3 mg C L^{-1}, 4.3 – 11.9) for all Brazilian biomes, but significant lower in the Amazonian Forest (3.8 mg C L^{-1}, 2.7 – 5.8) compared to the tropical coast (13.4 mg C L^{-1}, 6.1 – 32.8; Figure 2b; Dunn's test, $p < 0.05$). Most lakes (approximately 83% of raw data) showed surface waters supersaturated in CO_2 relative to atmospheric equilibrium (pCO_2 in atmospheric equilibrium of 403μatm, according Tans and Keeling 2014; data available in www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global), with much higher pCO_2 values in Amazonian lakes (7,956 μatm, 3,033 – 11,346) compared to subtropical coastal lakes (900 μatm, 391.3 – 3,212; Figure 2c; Dunn's test, $p < 0.05$).

The pCO_2 in surface waters of Brazilian lakes was independent of DOC concentrations (Linear regression for raw data, $p > 0.05$, Figure 3a). After correcting our data and Sobek data with the contribution of organic acids on TA and subsequent pCO_2 data, using the fitted linear regression for the median values of the relative difference between calculated and measured pCO_2 with pH, both groups continuous with the same pattern observed before (not significant relationship for Tropical data ($p > 0.05$, $n = 194$) and positive relationship for Sobek dataset ($pCO_2 = 45{,}70 \pm 1{,}84 \times DOC + 623{,}7 \pm 18{,}83$, $R^2= 0{,}12$, $p <0{,}0001$, $n = 4433$), figure 4a and 4b).

Even after correcting our data and Sobek data with the contribution of organic acids on TA and subsequent pCO_2 data, using the fitted linear regression for the averages values of the relative difference between calculated and measured pCO_2 with pH and medians and average values with DOC, we continuous not observing a positive relationship between pCO_2 and DOC for Brazilian data (see more detail in support material). The range of pCO_2 for a similar DOC range in Brazilian lakes was larger than that reported by Sobek et al., [2005] for data set dominated by high-latitude cold lakes, despite the number of lakes in their data set being much larger.

4.Discussion

The Brazilian lakes sampled here were characterized by a prevalence of CO_2 supersaturation, consistent with general trends for lakes [e.g. Cole et al., 1994, Algesten et al., 2005] and earlier reports for tropical lakes [Marotta et al., 2009]. The very high $p\mathrm{CO_2}$ observed here, in median 900 and 8300 µatm for subtropical and Amazon lake waters (respectively) are consistent with those reported earlier for the Amazon River and tributaries (2,000 - 12,000 µatm; Richey et al., [2002]), Amazon floodplain lakes (3,000 - 4,898 µatm; Rudorff et al., [2012]), Pantanal lakes and wetlands (2,732 - 10,620 µatm; Hamilton et al., [1995]), coastal lakes (768 - 9,866 µatm; Kosten et al., [2010]; 361 - 20,037 µatm; Marotta et al., [2010b]), and global values for tropical lakes (1,255 - 35,278 µatm; Marotta et al., [2009]), reservoirs (1,840 µatm; Aufdenkampe et al., [2011]) and wetlands (3,080 - 6,170 µatm; Aufdenkampe et al., [2011]).

The not significant (Figure 3a and 4a) or weakly negative relationship (support material) between DOC and $p\mathrm{CO_2}$ reported here for warm-low latitude lakes contrasted with significant positive relationships derived from previous datasets dominated by high-latitude lakes [Houle, 1995; Prairie et al., 2002; Jonsson et al., 2003; Sobek et al., 2005; Roehm et al., 2009; Lapiere and del Giorgio, 2012; Larsen et al., 2012]. The results presented show that warm-low latitude lakes range widely in $p\mathrm{CO_2}$, reaching very high values, but tend to have comparatively more uniform DOC concentrations.

Tropical conditions based on higher annual temperatures and solar incidence typically increases the aquatic primary productivity activity [Paerl and Huisman 2008] that releases into waters the DOC produced by the CO_2 uptake of algae and submerged plants [Staehr and Sand Jansen 2007], that can withstand a negative variation in the $p\mathrm{CO_2}$ with an increase in the DOC concentration. The contrasting not-significant or weak negative relationship between pCO2 and DOC in warm Brazilian lakes here with respect to that positive relationship for cold lake waters from the data set of Sobek al. (2005), suggests a temperature dependence of the $p\mathrm{CO_2}$ and DOC correlation in global lakes.

In conclusion, the finding that $p\text{CO}_2$ does not increase with DOC concentration in Brazilian tropical lakes rejects the hypothesis that DOC serves as a universal predictor for $p\text{CO}_2$ in lake waters [Larsen et al., 2012]. Even discounting a possible artifact of the method that could be causing an overestimation in the values of $p\text{CO}_2$, or considering the contribution of organic acids on the alkalinity, the pattern of no relationship between DOC and $p\text{CO}_2$ in the Tropical lakes was strongly confirmed. Despite limitations in the method of measuring the $p\text{CO}_2$, our work is important because it adds to the literature a data set about DOC and $p\text{CO}_2$ of tropical lakes so far not included in the global calculations until now. Therefore, our results suggest potentially important latitudinal differences from depositional aquatic environments, whose causes still need to be better addressed to improve accuracy of global C cycle models.

Authors Contribution

All authors contributed to the study design, interpreted data and wrote or commented the manuscript. L. P. and H. M. performed the sampling and sample analyses.

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References

Abril, G., Bouillon, S., Darchambeau, F., Teodoru, C., Marwick, T., Tamooh, F., Ochieng Omengo, F., Geeraert, N., Deirmendjian, L., Polsenaere, P., and Borges, A. Large overestimation of $p\text{CO}_2$ calculated from pH and alkalinity in acidic, organic-rich freshwaters. Biogeoscience, 12, 67-78, 2015.

Ab`Saber, A., Os Domínios de Natureza no Brasil: Potencialidades paisagísticas, Ateliê editorial Brazil, 2003.

Algesten, G., Sobek, S., Bergstrom,A., Jonsson, A., Tranvik, L. And Jansson, M., Contribution of sediment respiration to summer CO_2 emission from low productive boreal and subartic lakes, Microb. Ecol., 50, 529-535, 2005.

Aufdenkampe, A., Mayorga, E., Raymond, P., Melack, J. and Doney, S., Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere, Front. Ecol. Environ., 9, 1, 53-60, 2011.

Barreto, W. , Interpretation of Seasonal Variation of Metals and Abiotic Properties in a Tropical Lake Using Multivariate Analysis, Anal. Sci., 21 (3), 209-214, 2005.

Chambers, J., Higuchi, N., Schimel, J., Ferreira, L. and Melack, J., Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon, Oecologia, 122, 380-388, 1999.

Chellappa, N., Câmara, F. and Rocha, O., Phytoplankton community: indicator of water quality in the Armando Ribeiro Gonçalves Reservoir and Pataxó Channel, Rio Grande do Norte, Brazil, Braz. J. Biol., 69, 241-251, 2009.

Cole, J. J., Caraco, N. F., Kling, G. W. and Kratz, T. K., Carbon-Dioxide Supersaturation in the Surface Waters of Lakes, Science, 265, 1568-1570, 1994.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J. And Melack, J., Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget, Ecosystems, 10, 171-184, 2007.

Costa, M.:As macrófitas aquáticas da região litorânea de tres lagoas laterais do rio Parapanema na zona de sua desembocadura na Represa de Jurumim (SP), PhD thesis, São Paulo University, Brazil, 2000.

Davidson, E. A., and Artaxo, P., Globally significant changes in biological processes of the Amazon Basin: results of the Large-scale Biosphere-Atmosphere Experiment, Global Change Biol., 10 (5), 519-529, 2004.

Davidson, E. and Janssens, I., Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature, 440, doi:10.1038/nature04514, 2006.

Dillon, M. E., Wang, G. and Huey, R. B., Global metabolic impacts of recent climate warming, Nature, 467, 704-788, 2010.

Downing, J.A., Praire, Y.T., Cole, J.J., Duarte, C.M., Tranvik, L.J., Stiegl, R.G., McDowell, W.H., Kortelainen, P., Caraco, N.F., Melack, J.M. and Middleburg, J., The global abundance and size distribution of lakes, ponds, and impoundments, Limnol. Oceanogr., 51, 2388-2397, 2006.

Downing, J. A., Cole, J. J., Middelburg, J. J., Striegl, R. G. and Duarte, C. M., Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century, Glob. Biogeochem. Cy., 22, GB1018, doi:10.1029/2006GB002854, 2008.

Duarte, C. M. and Prairie, Y. T., Prevalence of heterotrophy and atmospheric CO_2 emissions from aquatic ecosystems, Ecosystems, 8, 862-870, 2005.

Duarte, C. M., Middelburg, J. J. and Caraco, N., Major role of marine vegetation on the oceanic carbon cycle, Biogeosciences, 2, 1-8, 2005.

Esteves, B., Limnological variables and nutritional content of submerged aquatic macrophytes in a tropical lagoon. (Lagoa do Campelo), Acta Limnologica Brasiliensis, 22 (2), http://dx.doi.org/10.4322/actalb.02202008, 2010.

Farjalla, V. F., Amado, A. M., Suhett, A. L., and Meirelles-Pereira, F., DOC removal paradigms in highly humic aquatic ecosystems, Environm. Sci. and Pol. Res. 16, 531-538, 2009.

Gudasz, C., Bastviken, D., Steger, K., Premke, K. and Sobek, S., Temperature-controlled organic carbon mineralization in lake sediments, Nature, *466*, 478- 481, 2010.

Hamilton, S. K., Sippel, S.J. and Melack, J.M., Oxygen depletion and carbon dioxide and methane production in waters of the Pantanal wetland of Brazil. Biogeochem. 30, 115-141, 1995.

Hamilton, S. K., Sippel S. J. and Melack, J. M., Comparison of inundation patterns among major South American floodplains, Journ. of Geophysic. Res., 107, D20, 8038, doi:10.1029/2000JD000306, 2002.

Hanson, P., Pace, M., Carpenter, C., Cole, J. and Stanley, E., Integrating Landscape Carbon Cycling: Research Needs for Resolving Organic Carbon Budgets of Lakes, Ecosystems, DOI: 10.1007/s10021-014-9826-9, 2014.

Henriques, R.P.B., Araújo, D.S.D. and Hay, J.D., Descrição e classificação dos tipos de vegetação da restinga de Carapebús, Rio de Janeiro. Rev. Bras. Bot. 9: 173 – 189, 1986.

Houle, D., Carigan, R., Lachance, M. and DuPont, J., Dissolved organic carbon and sulfur in southwestern Québec lakes: Relationships with catchment and lake properties, Limnol. Oceanogr., 40, 710-710, 1995.

Jonsson, A, Karlsson, J. and Jansson, M., Sources of carbon dioxide supersaturation in clearwater and humic lakes in Northern Sweden, Ecosystems, 6, 224-235, 2003.

Kosten, S., Roland, F., Da Motta Marques, D., Van Nes, E., Mazzeo, N., Sternberg, L., Scheffer, M. and Cole, J., Climate-dependent CO_2 emissions from lakes, Glob. Biogeochem.Cy., 24, 2010.

Junk, W. J. and Nunes de Cunha, C., Pantanal: a large South American wetland at a crossroads, Ecol. Eng., 24, 391- 401, 2005.

Lapierre, J. F. and del Giorgio, P. A., Geographical and environmental drivers of regional differences in the lake $p\mathrm{CO}_2$ versus DOC relationship across northern landscapes, Biogeosciences., 117, G03015, doi: 10.1029/2012JG001945, 2012.

Larsen, S., Andersen, T. and Hessen, D., The $p\mathrm{CO}_2$ in boreal lakes: Organic carbon as a universal predictor?, Glob. Biogeochem. Cy., 25, GB2012, doi:10.1029/2010GB003864, 2012.

López-Urrutia, Á. and Morán, X. A. G., Resource limitation of bacterial production distorts the temperature dependence of oceanic carbon cycling, Ecology, 88, 817–822, 2007.

Mariot, M., Dudal, Y., Furian, S., Sakamoto, A., Valles, V., Valls, V., Fort, M. and Barbiero, L., Dissolved organic matter fluorescence as a water-flow tracer in the tropical wetland of Pantanal of Nhecolândia, Brazil, Sci. Total Environm., 388, 184-193, 2007.

Marotta, H., Duarte, C. M., Sobek, S. and Enrich-Prast, A., Large CO_2 disequilibria in tropical lakes, Glob. Biogeochem. Cy., 23, 2009.

Marotta, H., Duarte, C. M., Meirelles-Pereira, F., Bento, L., Esteves, F. A. and Enrich-Prast, A., Long-term variability of CO_2 in two shallow tropical lakes experiencing episodic eutrophication and acidification events, Ecosystems, 13, 382–392, 2010a.

Marotta, H., Duarte, C. M., Pinho, L. and Enrich-Prast, A., Rainfall leads to increased $p\mathrm{CO}_2$ in Brazilian coastal lakes, Biogeosciences, 7, 1607-1614, 2010b.

Marotta, H., Pinho, L. Gudasz, C., Bastviken, D., Tranvik, L. and Enrich-Prast, A., Greenhouse gas production in low-latitude lake sediments responds strongly to warming, Nat. Clim. Change, 4, 467-470, 2014.

McDonald, C., Rover, J., Stets, E. and Striegl, R., The regional abundance and size distribution of lakes and reservoirs in the United States and implications for estimates of global lake extent, Limnol. Oceanogr., 57, 597-606, 2012.

Ometto, J. P. H. B., Nobre, A., Rocha, H., Artaxo, P. and Martinelli, L., Amazonia and the modern carbon cycle: lessons learned, Oecologia, 143, 483-500, 2005.

Paerl, H. and Huisman, J., Blooms like it hot, Science, 320, 57-58, 2008.

Pagioro, T., Influence of the decomposition of Eichhornia azurea on selected abiotic limnological variables of different environments of the floodplain of the high Paraná River, Acta Limnol. Bras., 11 (2), 157-171, 1999.

Pereira, E. A.: Limnologia de uma lagoa da região norte fluminense. Lagoa do Açu, Campos/ São João da Barra, RJ, PhD thesis, Federal University of Rio de Janeiro, Brazil, 2002.

Petrucio, M., Barbosa, F. and Furtado, A., Bacterioplankton and phytoplankton production in seven lakes in the Middle Rio Doce basin, south-east Brazil, Limnologica, 36 (3), 192-203, 2006.

Por, F., The Pantanal of Mato Grosso (Brazil) - World's Largest Wetlands, Klume Academic Publishers, Brazil, 1995.

Prairie, Y., The summer metabolic balance in the epilimnion of southeastern Quebec lakes, Limnol. and Oceanogr., 47, 1, 316-321, 2002.

Prairie, Y. T., Carbocentric limnology: looking back, looking forward, Canadian Journal of Fisheries and Aquatic Sci., 65(3), 543-548, 2008.

Raymond, P., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P. and Guth, P., Global carbon dioxide emissions from inland waters. Nature, 503, 355- 359, 2013.

Regaudie-de-Gioux A and Duarte C.M., Temperature dependence of planktonic metabolism in the ocean, Glob. Biogeochem. Cycles 26:GB1015. 2012.

Richey, J. E., Melack, J. M., Aufdenkampe, A. K., Ballester, V. M., and Hess, L. L., Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2, Nature, 416(6881), 617–620, 2002.

Rocha, R.: Limnologia comparativa e preditiva de rios e lagoas da planície de inundação do alto rio Paraná (PR/MS-Brasil), Phd. Thesis, Maringa State University, Brazil, 2003.

Roehm, C., Prairie, Y. T. and del Giorgio, P., The $p$$CO_2$ dynamics in lakes in the boreal region of northern Québec, Canada, Global Biogeochem. Cy., 23, GB3013, doi:10.1029/2008GB00329, 2009.

Romeiro, F.: Bioensaios de decomposição anaeróbia de macrófitas aquáticas da lagoa do Óleo (Estação Ecológica de Jataí, Luiz Antônio – SP. Msc. Dissertation, São Carlos University, Brazil, 2005.

Rudorff, C. M., Melack, J. M.; MacIntyre, S.; Barbosa, C. C. F.; and Novo, E. M. L. M., Seasonal and spatial variability of CO_2 emission from a large floodplain lake in the lower Amazon, J. Geophys. Res., 117, G01002, doi: 10.1029/2011JG001699, 2012.

Scarano, F., Structure, function and floristic relationships of plant communities in stressful habitats marginal to the Brazilian Atlantic rainforest, Annals of botan., 90, 4, 517-524., 2002.

Silva, F.: Dinâmica espaço-temporal da comunidade de bactérias planctonicas em lagoas costeiras do norte fluminense, Msc. Dissertation, Federal University of Rio de Janeiro, Brazil, 2007.

Stumm, W. and Morgan, J. J., Aquatic chemistry: chemical equilibria and rates in natural waters, vol 3. Wiley, New York, 1996.

Sobek, S., Tranvik, L. J. and Cole, J. J., Temperature independence of carbon dioxide supersaturation in global lakes, Global Biogeochem. Cy., 19, GB2003, doi:10.1029/2004GB002264, 2005.

Sobek, S., Tranvik, L., Prairie, Y., Kortelainen, P. and Cole, J., Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes, Limnol. Oceanogr., 52, 1208-1219, 2007.

Spyres, G., Nimmo, M., Worsfold, P., Achterberg, E., Miller, A., Determination of dissolved organic carbon in seawater using high temperature catalytic oxidation techniques, Trends in Analytic Chem., 19, 8, 498-506, 2000.

Staehr, P. and Sand-Jansen, K.,Temporal dynamics and regulation of lake metabolism, Limnol. and Oceangr. 52 (1), 108-110, 2007.

Steinberg, C. E. W., Kamara, S., Prokhotskaya, V., Manusadzianas, L., Karasyova, T., Timofeyev, M., Jie, Z. Paul, A., Meinelt, T., Farjalla, V., Matsuo, A., Burnison, B. and Menzel, R., Humic substances in the environment with an emphasis on freshwater systems, Environm. Sci. Pollut. Res. Int., 15, 15-16, 2006.

Tans, P. and Keeling, R., Trends in Atmospheric Carbon Dioxide. National Oceanic and Atmospheric Administration Earth System Research Laboratory Global Monitoring Division; Scripps Institution of Oceanography. http://www.esrl.noaa.gov/gmd/ccgg/trends/. (Accessed 19.05.15).

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larsen, S., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Prairie, Y., Renwick, W.H., Roland, F., Sherman, B.S., Schindler, D.W., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E. and Weyhenmeyer, G.A., Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanogr., 54, 2298-2314, 2009.

Wadham, J., Arndt, S., Tulaczyk, S., Stibal, M., M. Tranter, M., Telling, J., Lis, G., Lawson, E., Ridgwell, A., Dubnick, A., Sharp, M., Anesio, A. and Butler, C., Potential methane reservoirs beneath Antarctica, Potential methane reservoirs beneath Antarctica, Nature, 488, 633-637, 2012.

Waechter, J. L., Epiphyticorchids in eastern subtropical South America. Proc. 15th World Orchid Conference. Naturalia Publications, pp. 332-341, 1998.

Wang, Z. A., Bienvenu, D. J., Mann, P.J., Hoering, K.A., Poulsen, J. R., Spencer, R.G. and Holmes, R. M., Inorganic carbon speciation and fluxes in the Congo River. Geophysic. Res. Letters, 40, 511-516, 2013.

Weiss, R. F., Carbon Dioxide in water and seawater: The solubility of non-ideal gas, Mar. Chem., 2, 203-215, 1974.

Wohlers, J., Engel, A., Zollner, E., Breithaupt, P., Jurgens, K., Hoppe, H., Sommer, U. and Riebesell, U., Changes in biogenic carbon flow in response to sea surface warming. PNAS, 106,17, 7067-7072, 2008.

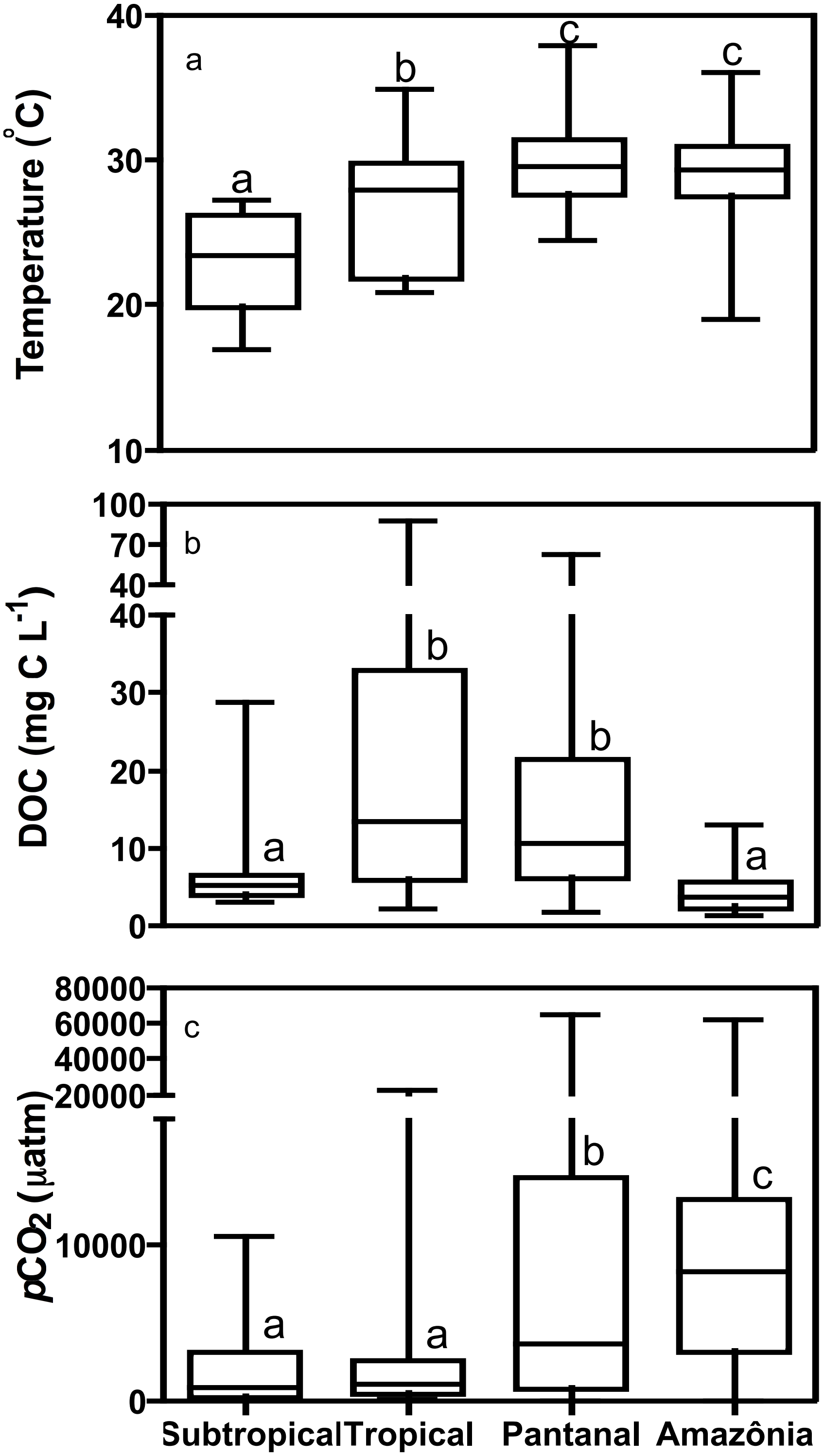
Ulloa, V., Density and biomass of planktonic rotifers in different habitats in upper Paraná River (PR, Brazil), Acta Limnol. Bras., 16 (3), 281-292, 2004.

Xenopoulos, M. A., Lodge, D. M., Frentress, J., Kreps, T. A. and Bridgham, S. D., Regional comparisons of watershed determinants of dissolved organic carbon in temperate lakes from the Upper Great Lakes region and selected regions globally, Limnol. Oceanogr., 48, 2321-2334, 2003.

Zar, J. H., Biostatistical analysis, 3 ed., Prentice Hall., New Jersey, 1996.

Figures and subtitles

Figure 1. Geographic location of Brazilian lakes sampled at different biomes (IBGE 2004, available in ftp://geoftp.ibge.gov.br/mapas_tematicos/mapas_murais/biomas): Amazonia Forest (vertical lines), Pantanal Floodplain (dark gray), and Atlantic Forest (gray; Tropical and Subtropical costal lakes).


Temperature (°C)
40
30
20
10
a
a
b
c
c
DOC (mg C L-1)
100
70
40
40
30
20
10
0
b
a
b
b
a
pCO2 (μatm)
80000
60000
40000
20000
10000
0
c
a
a
b
c
Subtropical
Tropical
Pantanal
Amazônia

434

435

Figure 2. Values of (A) temperature (ºC), (B) DOC concentrations (mg C L^{-1}) and (C) pCO_2 concentration (µatm) of Brazilian lakes sampled from different biomes, as defined by (SUBT) Subtropical Coastal lakes (n = 37), (TROP) Tropical coastal lake (n = 63), (PANT) Pantanal Floodplain (n = 58) and (AMAZ) Amazonia Forest (n = 67). The line depicts the median. The boxes show the quartiles, and the whiskers mark the 10% and 90% percentiles. Different lowercase letters near the boxplot indicate significant statistic differences between the groups (Kruskall-Wallis followed by Dunn`s multiple comparison post hoc test, $p < 0.05$).

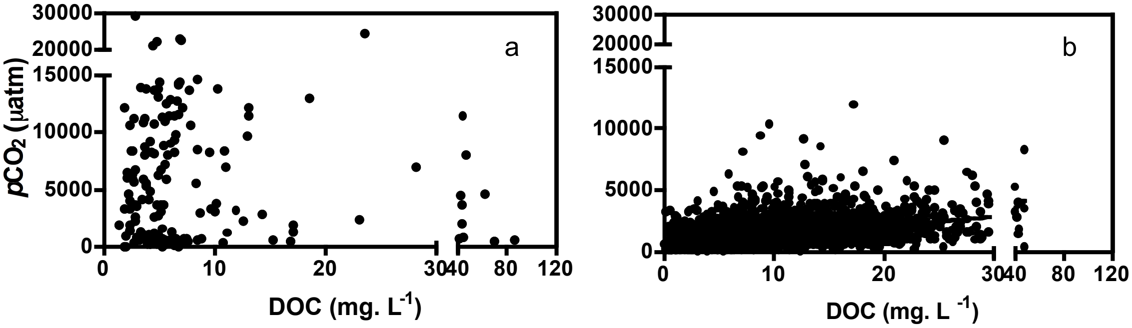


Figure 3. The relationship between *p*CO2 values and DOC concentrations for surface lake waters at (a) warm low latitudes from our compilation, and (b) cold high latitudes from the data set of Sobek et al. (2005). Each circle represents integrated values for each lake (see details in the Methods section). The solid line represents the fitted linear regression equation for cold lakes (*p*CO2 [µatm] = 2.67 + 0.414 log DOC [mg C L-1]; $R^2 = 0.26$; $p < 0.05$, n = 4554). A non-significant linear regression was observed for warm low-latitude lakes (p>0,05, n = 194).

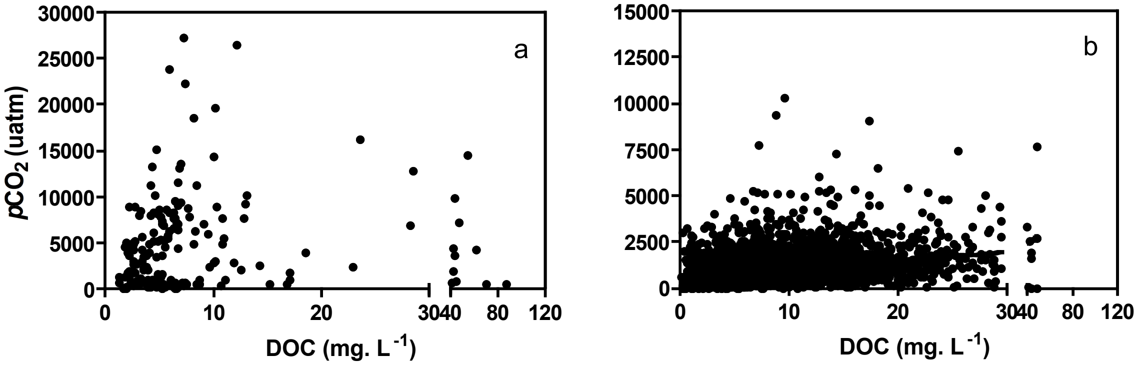


Figure 4: The relationship between *p*CO2 values and DOC concentrations for surface lake waters after correcting the contribution of organic acids on TA and subsequent *p*CO2 data, compiled as described in Figure 3 and using corrections from the fitted linear regression for the median values of the relative difference between calculated and measured *p*CO2 with pH (see methods for details; data for corrections available in Abril et al., 2015). The solid line represents the fitted linear regression equation for cold high-latitude lake waters (*p*CO2 = 45,70 ± 1,84 x DOC + 623,7 ± 18,83, R^2= 0,12, p <0,0001, n=4433). A non-significant linear regression was observed for warm low-latitude lakes (p>0,05, n = 194).