Biogeosciences, 7, 1607–1614, 2010
www.biogeosciences.net/7/1607/2010/
doi:10.5194/bg-7-1607-2010

Biogeosciences

Rainfall leads to increased pCO$_2$ in Brazilian coastal lakes

H. Marotta[1,2], **C. M. Duarte**[2], **L. Pinho**[1], **and A. Enrich-Prast**[1]

[1]Biogeochemistry Laboratory, Department of Ecology, Universidade Federal do Rio de Janeiro (UFRJ), Cidade Universitária s/n, 68020 Rio de Janeiro, Brazil
[2]Department of Global Change Research, IMEDEA (CSIC-UIB), Instituto Mediterráneo de Estudios Avanzados, Miquel Marqués 21, 07190 Esporles, Spain

Received: 28 November 2009 – Published in Biogeosciences Discuss.: 15 December 2009
Revised: 8 April 2010 – Accepted: 14 April 2010 – Published: 18 May 2010

Abstract. The variation of partial pressure of CO$_2$ (pCO$_2$), pH, salinity and dissolved organic carbon (DOC) in surface waters of 12 coastal Brazilian lakes was examined following periods of contrasting rainfall. Periods of high rainfall were followed by a large, almost 10 fold, increase in pCO$_2$ and a one unit decrease in pH in the lakes, whereas no consistent changes in DOC were observed. CO$_2$ emissions to the atmosphere from the Brazilian coastal lakes studied here were highly enhanced, on average, from $28.5 \pm 6.0\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ in dry periods to $245.3.1 \pm 51.5\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ following periods of heavy rainfall. The increased inputs of pCO$_2$ following periods of high rainfall are believed to be derived from increased inputs of pCO$_2$ from groundwaters to the lakes.

1 Introduction

Although inland aquatic ecosystems occupy a small fraction of the continents (2 to 4%; Downing et al., 2006), these ecosystems can affect regional carbon balances, as they tend to support higher net carbon fluxes per unit area than those in surrounding terrestrial ecosystems (Cole et al., 2007; Tranvik et al., 2009). The disproportionate role of lakes in the carbon balance of landscapes derives from their role as recipients of a substantial fraction of the carbon produced within the watershed (Lennon, 2004; Sobek et al., 2005), and transported to lakes through surface runoff and groundwater flow, which are intensified following rainfall events (Schindler, 1978).

Terrestrial organic carbon, though relatively refractory (Hopkinson et al., 1998), plays an important role in lakes, where it partially supports aquatic food webs (Pace et al., 2004), metabolism (Cole et al., 2000) and contributes to the prevalent carbon dioxide (CO$_2$) supersaturation of lake waters (Sobek et al., 2005). Allochthonous inputs of CO$_2$ can also contribute to maintain the partial pressure of carbon dioxide (pCO$_2$) above equilibrium with the atmosphere in aquatic ecosystems (Raymond and Cole, 2003). CO$_2$ enrichment of lake waters may closely follow the precipitation pattern (Rantakari and Kortelainen, 2005), possibly reflecting the associated inputs of surface and groundwater waters containing high concentrations of terrestrial organic and inorganic carbon (cf. Cole et al. 2007).

Tropical coastal lakes in Brazil are typically small, shallow, and broadly distributed in watersheds with important components of Restinga, the characteristic vegetation of Atlantic Tropical Forest, occupying extensive areas of sand plain along the coastline. This vegetation is a major source of carbon to these lakes, which waters are often highly colored (Amado et al., 2007). Recent analyses have shown Brazilian lakes to be highly supersaturated in CO$_2$ (Marotta et al., 2009), supported by high inputs of terrestrial-derived carbon to these lakes. Groundwater plays an important role in the water budget and inputs of materials to Brazilian coastal lakes, a role that can be intensified by high rainfall, due to low water retention by the sandy soils in their watershed (Farjalla et al., 2002). Indeed, pCO$_2$ in Brazilian coastal lakes have been shown to vary greatly and synchronously over time (Marotta et al., 2010), suggesting weather-control of this property. Because temperature shows little temporal variability in this tropical region, rainfall, which may affect the discharge of groundwater and the associated inputs of carbon to the lakes and that vary greatly over time, may be the driver behind this synchronous pCO$_2$ variability. However, the role of rainfall in accounting for variability in CO$_2$ in these ecosystems has not yet been tested.

Correspondence to: A. Enrich-Prast
(aenrichprast@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

We examined here the variability in surface $p\mathrm{CO}_2$, pH, salinity and DOC in a series of coastal Brazilian lakes to test the hypothesis of a relationship between variability in $p\mathrm{CO}_2$ and that in rainfall in these lakes.

2 Material and methods

2.1 Study area

The coastal lakes studied are located in Rio de Janeiro state, characterized by warm temperatures, ranging from a minimum monthly average temperature of 20.7 °C in July to a maximum of 26.2 °C in February (INMET, 1992). The mean minimum and maximum rainfall are typically observed in August (38 mm) and December (182 mm; INMET, 1992), but show high inter-annual variation (Carmouze et al., 1991).

The 12 studied lakes (Fig. 1) are situated in the National Park of Restinga de Jurubatiba, one of the most important protected areas with coastal lakes in Brazil. This conservation area has many small lakes separated from the sea by sandbars along the shoreline, which may open up during episodic events, including extreme rainfall and sea storms, or human intervention.

The studied lakes stretch along a 40 Km strip of coastline (22°00′ and 22°23′ S and 41°15′ and 41°45′ W; Fig. 1), are small (area $<5\,\mathrm{km}^2$; Table 1), shallow (maximum depth varying from 0.8 to 4.0 m), and affected by saltwater intrusions resulting in brackish-saline waters (salinity range from 2 to 33). Most lakes of this region do not have surface freshwater inlets but are fed by groundwater. Rainfall exerts an important dynamic control on lake depth through groundwater inputs, which contribute high DOC (Suzuki et al., 1998). and CO_2 inputs, as groundwaters are highly supersaturated in CO_2 (Suzuki et al., 1998).

2.2 Study Design

The general sampling strategy involved a series of sampling events between 2003 and 2006, each involving measurements along 24 h cycles to characterise daily variability in $p\mathrm{CO}_2$ and preceded by contrasting weekly-accumulated rainfall. Sampling effort at Lake Carapebus was more intense, with $p\mathrm{CO}_2$, pH, salinity and temperature analyzed 9 times over two consecutive daily cycles (06:00 p.m., 06:00 a.m., 10:00 a.m., 02:00 p.m., 06:00 p.m. the following day) and only once for DOC concentrations in each sampling event (N = 6 samplings events between 2003 and 2004). Two sampling stations, characterized by a similar oligo-mesotrophic status during this period (about $0.8\,\mu\mathrm{mol\,L}^{-1}$ of total phosphorus and $5\,\mu\mathrm{g\,L}^{-1}$ of chlorophyll-*a* concentrations), were analyzed in this lake. A station colonized by submerged aquatic plants (macrophyte covered), mainly *Potamogetum stenostachys* with a mean ± SE standing crop of $1430 \pm 200\,\mathrm{g\,m}^{-2}$ (N = 21 quadrats between 2004 January and July), and a station devoid of macrophytes (open waters).

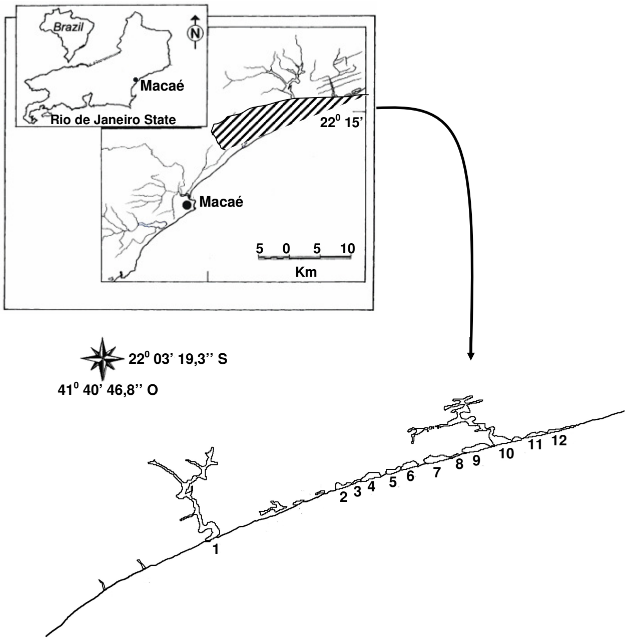

Fig. 1. Location of the studied lakes (1) Carapebus, (2) Garças, (3) Peri-peri 1, (4) Peri-peri 2, (5) Maria Menina, (6) Robalo, (7) Visgueiro, (8) Catingosa, (9) Pires, (10) Preta, (11) Barrinha and (12) Casa Velha.

Table 1. General characteristics of the studied lakes.

Lakes	Total P* ($\mu\mathrm{mol\,L}^{-1}$)	Colour* (at 430 nm)	Area (km^2)
Garças	0.4–0.5	0.026–0.089	0.42
Peri-peri 1	0.7–0.9	0.036–0.040	0.14
Peri-peri 2	0.8–1.0	0.080–0.138	0.83
Maria Menina	0.5 – 0.7	0.019-0.089	0.24
Robalo	0.4–0.6	0.014–0.026	0.85
Preta	0.2–0.7	0.217–0.307	2.19
Pires	0.4–1.0	0.071–0.075	0.92
Catingosa	0.5–0.7	0.013–0.049	0.09
Visgueiro	0.3–1.0	0.021–0.037	1.18
Casa Velha	0.2–0.5	0.044–0.068	0.54
Barrinha	0.8–1.1	0.049–0.087	0.24
Carapebus	0.6–1.1	0.009–0.028	4.33

* Range considering the sampling events in each lake.

A total of 11 additional oligo to mesotrophic (total phosphorus below $1.1\,\mu\mathrm{mol\,L}^{-1}$, Table 1) coastal lakes were sampled in the National Park of Restinga de Jurubatiba. $p\mathrm{CO}_2$, pH, salinity and temperature in surface waters were simultaneously analyzed 4 times over a daily cycle (06:00 p.m., 06:00 a.m., 12:00 a.m. and 06:00 p.m. the following day) and only once per daily cycle for DOC concentrations, in each of two sampling events preceded by dry and rainy periods, both in 2006.

2.3 Analytical Methods and $p\mathrm{CO}_2$ Calculations

Surface water samples were immediately analyzed for pH and alkalinity. Temperature and salinity were measured in situ with a calibrated YSI-30 Thermosalinometer. At the laboratory, pre-filtered (0.7 µm, Whatman GF/F) water samples were acidified to pH <2.0 and analyzed for DOC concentrations using high-temperature catalytic oxidation on a Shimadzu TOC-5000 Analyzer. CO_2 concentrations and dissolved inorganic carbon concentrations (DIC) were calculated from pH and alkalinity measurements after correction for temperature, altitude and ionic strength following Cole et al. (1994) and Weiss (1974). pH was measured with a precision of 0.01 pH units using a calibrated Analion PM 608 pH meter and total alkalinity by Gran's titration (APHA, 1992). $p\mathrm{CO}_2$ was calculated using Henry's law, as the ratio between the CO_2 concentration and Henry's constant for this gas at a given temperature and salinity.

Data on rainfall were obtained from the Brazilian Aerospace Technical Center (CTA, São José dos Campos). Rainfall data were aggregated as the cumulative rainfall in the week preceding each sampling event, encompassing the time lag between rainfall events and hydrological inputs as well as the time scales for responses of lake metabolism to perturbations (Staehr and Sand-Jensen, 2007).

Log-transformed data showed significant Gaussian distribution (Kolmogorov-Smirnov, $p<0.05$), homogeneity of variances (Bartlett, $p>0.05$) and significant pairing (F test, $p<0.05$). Hence, sampling events were compared using paired parametric tests with a significance of $p<0.05$ (Zar, 1996). We used paired t-test to compare two data sets or repeated measures one-way ANOVA followed by Tukey-Kramer test for multiple comparisons. All statistics were calculated using the software Graphpad Prism 4.0. Daily means of $p\mathrm{CO}_2$ were calculated in each sampling event and lake (two daily cycles in Lake Carapebus and only one in other lakes).

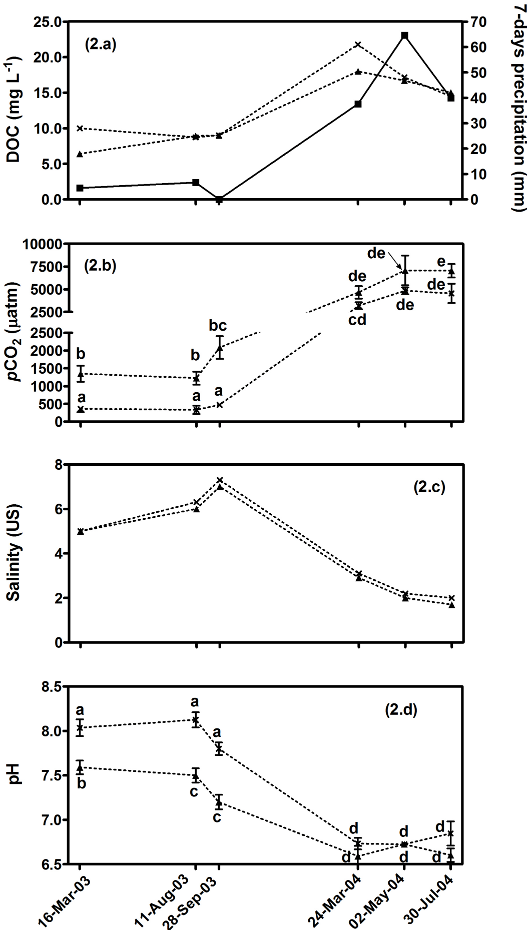

Fig. 2. Accumulated precipitation in the week preceding the sampling (full squares) and average DOC concentrations **(a)**, $p\mathrm{CO}_2$ **(b)**, salinity **(c)** and pH **(d)** in open waters (triangles) and macrophyte-covered (crosses) waters of Lake Carapebus along the studied period. Bars indicate standard errors and at least a letter shared by different dates indicates no significant differences (Tukey-Kramer, $p<0.05$) for pH and $p\mathrm{CO}_2$ among stations and sampling events.

3 Results

Daily variability in $p\mathrm{CO}_2$ (coefficient of variation = 68%) and pH (6.5 to 7.5) was substantial, and comparable in magnitude to as variability across lakes after dry or rainy periods (coefficient of variation = 75% and 6.5 to 8.0 respectively). However, the daily range between minimum and maximum $p\mathrm{CO}_2$ and pH were much larger, increasing from 3.5 to 50 fold and from 0.5 to 8 fold, respectively, following rainy periods in all studied lakes, except in Lake Carapebus, where the daily range in pH was comparable between both rainy and drier periods. The mean increase in maximum daily values of $p\mathrm{CO}_2$ following high weekly-accumulated precipitation was about 6 fold (paired t-test, $p<0.0001$), well above that experienced by minimum daily $p\mathrm{CO}_2$ values (about 85%; $p<0.05$, paired t-test).

The increase in weekly-accumulated rainfall at Lake Carapebus (Fig. 2) was coupled to great $p\mathrm{CO}_2$ enrichments (about 11 fold in the macrophyte covered station and 4 fold in the open water station), two-fold higher DOC concentrations, a decrease of 50% in salinity and a reduction in pH by 1.0 unit (Tukey-Kramer and paired t-test, $p<0.05$; Fig. 2 and Table 2). Indeed, there were strong positive relationships of lake $p\mathrm{CO}_2$ and DOC with respect to weekly-accumulated rainfall, which was negatively correlated with pH and salinity, in both Lake Carapebus stations (linear regression, $p<0.05$; Fig. 3). High rainfall also homogenised $p\mathrm{CO}_2$ within Lake Carapebus, as the high intra-ecosystem heterogeneity for $p\mathrm{CO}_2$ ($p\mathrm{CO}_2$ about 4 times higher in the open water compared to the station with submerged macrophytes) was reduced to a non-significant difference following intense rain. In contrast, the extent of variability in water temperature

Table 2. Daily-average values of pCO$_2$, DOC, pH and salinity after periods of high and low weekly-accumulated precipitation events for each studied lake, and the ratio of high rainfall to low rainfall values.

Lakes	7-days precipitation (mm)	pCO$_2$ (µatm)	DOC (mg L^{-1})	pH (US)	Salinity
Garças	1.2	871	17.7	8.4	33.2
	38.7	4419	23.0	7.8	32.2
	Ratio	*5.07*	*1.30*	*– 0.6*	*0.97*
Peri-peri 1	1.2	552	18.8	8.5	25.7
	38.7	8389	34.8	7.4	12.9
	Ratio	*15.20*	*1.30*	*– 1.1*	*0.50*
Peri-peri 2	1.2	1927	38.0	7.8	10.6
	38.7	6644	43.8	7.7	14.0
	Ratio	*3.45*	*1.15*	*– 0.1*	*1.32*
Maria Menina	1.2	1889	35.9	8.0	18.1
	38.7	6387	42.7	7.7	15.8
	Ratio	*3.38*	*1.19*	*0.3*	*0.87*
Robalo	1.2	1611	43.0	8.3	25.8
	38.7	13736	38.3	7.6	20.0
	Ratio	*8.53*	*0.89*	*– 0.7*	*0.77*
Preta	1.2	2115	39.0	7.6	3.3
	38.7	5950	42.0	7.3	4.5
	Ratio	*2.81*	*1.08*	*– 0.3*	*1.36*
Pires	1.2	1564	35.5	8.0	7.0
	38.7	5505	34.5	7.5	3.5
	Ratio	*3.52*	*0.97*	*– 0.5*	*0.50*
Catingosa	1.2	3446	Nc	7.8	20.6
	38.7	20037	40.1	7.1	20.5
	Ratio	*5.81*	–	*– 0.7*	*0.99*
Visgueiro	1.2	2643	37.6	8.0	21.8
	38.7	16672	37.8	7.2	22.1
	Ratio	*6.31*	*1.01*	*– 0.8*	*1.01*
Casa Velha	1.2	361	41.2	8.7	5.0
	38.7	1153	40.9	8.3	7.0
	Ratio	*3.19*	*0.99*	*– 0.4*	*1.40*
Barrinha	1.2	1167	42.9	8.2	4.9
	38.7	2684	43.1	7.8	6.5
	Ratio	*2.30*	*1.00*	*– 0.4*	*1.32*
CAR_ Macrophytes	0.0–6.7	386	9.1	7.9	6.0
	34.6–67.6	4203	17.9	6.8	2.2
	Ratio	*10.90*	*1.98*	*– 1.1*	*0.37*
CAR_ Open	0.0–6.7	1609	8.1	7.4	6.2
	34.6–67.6	5905	16.6	6.6	2.4
	Ratio	*3.67*	*2.05*	*– 0.8*	*0.39*

nc = not collected.

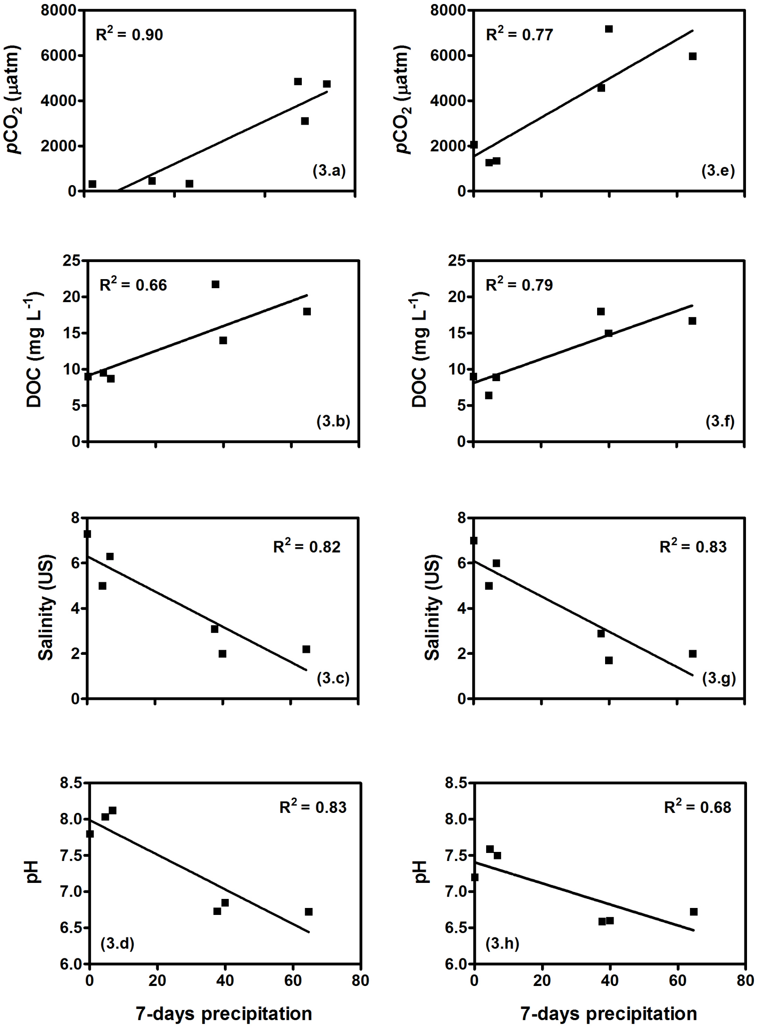

Fig. 3. The relationships between mean $p\mathrm{CO_2}$, DOC, salinity and pH with accumulated precipitation in the week preceding the sampling in the macrophyte covered (Figs. 3a, b, c, d) and open water (Figs. 3e, f, g and h) stations at Lake Carapebus. Solid lines represent significant linear regressions ($p < 0.05$).

was independent of the previous rainfall (linear regression, $p > 0.05$).

A pattern towards sharply increasing $p\mathrm{CO_2}$ and decreasing pH with increasing rainfall was also evident considering all remaining lakes sampled, with $p\mathrm{CO_2}$ increasing by 3 to 15 fold and pH decreasing from 0.1 to 1.1 units after rainy periods (Table 2). Lake $p\mathrm{CO_2}$ and pH were strongly correlated, within sampling events and for both sampling events combined (linear regression, $p < 0.05$; Fig. 4). In contrast, changes in DOC concentrations did not follow a consistent trend with rainfall across the 11 lakes sampled simultaneously (Table 2). There was no significant relationship between $p\mathrm{CO_2}$ and DOC within each sampling event or for both sampling events combined (linear regression, $p > 0.05$; Fig. 4).

Salinity fluctuations were not synchronous among the lakes in both sampling events, and changes in salinity were independent of those in $p\mathrm{CO_2}$ among lakes (linear regression, $p > 0.05$; Fig. 4). However, lakes with a higher decline in salinity following intense rainfall (like Peri-peri1 and Robalo) showed higher $p\mathrm{CO_2}$ enrichment in the rainy compared to the drier period (Table 2). Indeed, the observed changes in $p\mathrm{CO_2}$ in the 11 lakes sampled between the drier and rainier sampling events were significantly correlated with changes in salinity and pH (positive and negative, respectively), but not with fluctuations in DOC (Table 2 and Fig. 5, linear regression, significant $p < 0.05$). Another important driver of lake $p\mathrm{CO_2}$, water temperature, remained relatively uniform between both sampling events (21.5 ± 0.3 °C, mean ± SE) and was not also significantly related to the large differences of $\mathrm{CO_2}$ saturation observed in the lakes studied (t-test, $p > 0.05$).

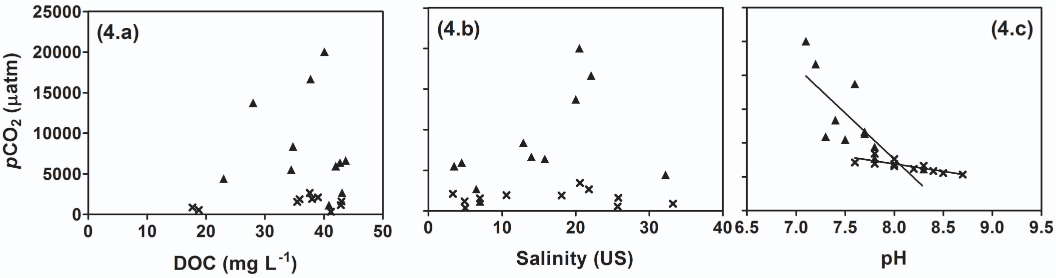

Fig. 4. The relationships of pCO_2 with **(a)** DOC, **(b)** salinity and **(c)** pH in 11 lakes sampled simultaneously within drier (crosses) and rainier (full triangles) sampling events. Only pH showed significant linear regressions ($p < 0.05$) with pCO_2 in each period ($pCO_2 = -2214\,\mathrm{pH} + 19{,}620$, $R^2 = 0.61$ for the drier one; $pCO_2 = -13{,}640\,\mathrm{pH} + 111{,}800$, $R^2 = 0.66$ for the rainier one), and combining both ($pCO_2 = -9823\,\mathrm{pH} + 82{,}090$, $R^2 = 0.60$).

4 Discussion

Most of the lakes examined had waters supersaturated in CO_2, acting therefore as CO_2 sources to the atmosphere in all sampling events. Only two lakes showed daily mean pCO_2 below atmospheric equilibrium (about 380 µatm). The lowest pCO_2 values were observed in the station colonized by submerged macrophytes in Lake Carapebus, consistent with the role of submerged vegetation as CO_2 sinks in natural waters (Krause-Jensen and Sand-Jensen, 1998).

Increased, weekly-accumulated, precipitation prompted considerable increase in pCO_2 and the amplitude of daily pCO_2 variability, despite minor changes in water temperature. Higher amplitude of diel CO_2 changes in lakes (Staehr and Sand-Jensen, 2007) might reflect increases in the metabolism of lake ecosystems (Richey et al., 2002). Here, the strong increase in mean and maximum daily pCO_2 values, well above those in the minimum daily pCO_2 values, resulted in broad daily pCO_2 oscillations following periods of high rainfall. This result confirms that intense rainfall may be correlated with CO_2 enhancements in small tropical lakes even one order of magnitude higher than previously reported for large boreal lakes (Rantakari and Kortelainen, 2005).

The positive relationship of pCO_2 with DOC, and negative relationship with pH and salinity, following periods of high rainfall at Lake Carapebus is consistent with evidence that terrestrial freshwater inputs enhance CO_2 production in lake ecosystems (Cole et al., 1994; Cole et al., 2007). It also confirms the potential role of rainfall on the inputs of terrestrial organic substrates to aquatic CO_2 production by respiration in lakes (Rantakari and Kortelainen, 2005).

Groundwater inputs have been shown to be important drivers of changes in coastal tropical lakes elsewhere (HerreraSilveira, 1996), and are a major vector of inputs of humic acids to the lakes studied here (Farjalla et al., 2002). The Restinga vegetation in the lake watershed provides abundant organic carbon to the soils, which can be entrained to groundwater along with the CO_2 derived from respiration of this organic carbon during periods of intense rainfall and eventu-

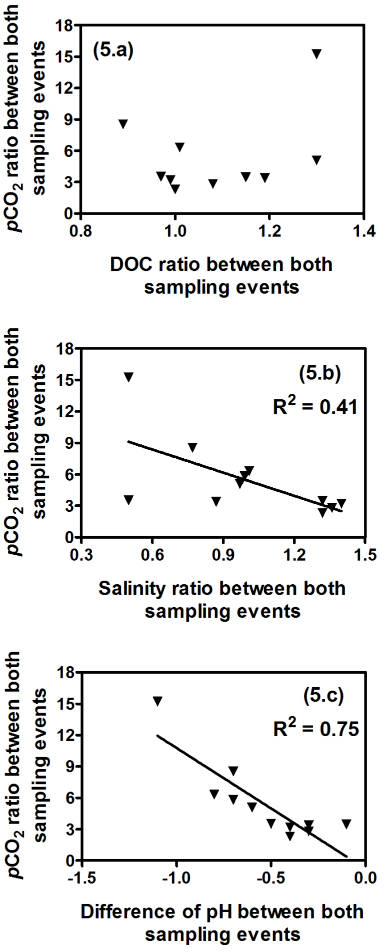

Fig. 5. The relationships of the variation rates, comparing the rainier sampling event to drier one, of pCO_2 with (Fig. 4a) DOC, (Fig. 4b) salinity and (Fig. 4c) pH in the 11 lakes sampled simultaneously. Solid lines represent the significant fitted regression equations ($p < 0.05$) for changes in salinity (variation rate in $pCO_2 = -7.4$ variation rate in salinity + 12.8, $R^2 = 0.41$) and pH (variation rate in $pCO_2 = -11.5$ variation rate in pH -0.8, $R^2 = 0.75$).

ally delivered to the lake (Marotta et al., 2010). Analysis of stable carbon isotopic signatures has also revealed that DOC in the lake waters in the study region largely represent allochthonous carbon from terrestrial sources delivered to the lake by groundwaters (Marotta et al., 2010). $p\mathrm{CO_2}$ values in groundwaters in the study region can reach very high values, e.g., up to 70,000 µatm or about 180 times higher than the equilibrium with the atmosphere (Suzuki et al., 1998), so that groundwater inputs can support large $p\mathrm{CO_2}$ emissions when ventilating in lake waters. Indeed, the high $\mathrm{CO_2}$ in groundwaters, along with the high concentration of terrestrial humic acids, account for the low pH of groundwaters (Jones and Mulholland, 1998), explain the general reduction in pH observed in the lakes studied following periods of intense rainfall.

The coupling between high rainfall and high $p\mathrm{CO_2}$ and a decrease in pH and salinity observed in Lake Carapebus was consistent with the changes observed in the 11 lakes sampled simultaneously after rainy events. In contrast, the lack of a significant relationship between the variability in $p\mathrm{CO_2}$ and DOC in these lakes indicates that strong $p\mathrm{CO_2}$ enrichment with increasing rainfall is not always accompanied by an increase in DOC. Indeed, there was no significant relationship between lake DOC and $p\mathrm{CO_2}$ in the lakes sampled here, in contrast to the general relationship observed at the global scale (Sobek et al., 2005). Yet, the broader daily variation in $p\mathrm{CO_2}$ following periods of intense rainfall indicates that ecosystem metabolism is enhanced following rainfall.

Our results confirmed the hypothesis and previous findings on the high $p\mathrm{CO_2}$ variability for tropical inland waters, suggesting a possible controlling role of rainfall. Here, large $p\mathrm{CO_2}$ enhancements in lake waters following increases in weekly-accumulated rainfall were even comparable to the variation observed among lakes (Marotta et al., 2009) and within lakes (Marotta et al., 2010), or that related to seasonal (Richey et al., 2002) and interannual (Marotta et al., 2010) changes in inland waters at low latitudes. The results presented demonstrate an important role of rainfall, and the subsequent groundwater inputs, in generating variability in $p\mathrm{CO_2}$ in the Brazilian coastal lakes studied, with a large increase in $p\mathrm{CO_2}$, and a decline in pH, following higher rainfall. The diel variability reported also suggests that intense rainfall also stimulates ecosystem metabolism conducive to broad variability in $p\mathrm{CO_2}$ along the day. Whereas groundwater contributes relatively small amounts of $\mathrm{CO_2}$ directly to the atmosphere (Cole et al., 2007), the ventilation of the high $\mathrm{CO_2}$ in groundwater may support intense $\mathrm{CO_2}$ emissions when entering lakes. Estimates of the $\mathrm{CO_2}$ emissions to the atmosphere from these lakes were derived following calculations in Cole and Caraco (1998), a $p\mathrm{CO_2}$ in equilibrium with the atmosphere of 380 µatm and the mean global wind velocity reported over land of $3.28\,\mathrm{m\,s^{-1}}$ (Archer and Jacobson, 2005). $\mathrm{CO_2}$ emissions from Brazilian coastal lakes studied here were enhanced, on average, almost 10 fold following intense rainfall, from an average ($\pm$ SE) of $28.5 \pm 6.0\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ in drier periods to $245.3 \pm 51.5\,\mathrm{mmol\,C\,m^{-2}\,d^{-1}}$ following heavy rain. These results suggest that precipitation and subsequent ventilation of groundwater $\mathrm{CO_2}$ at the lake-atmosphere interface may provide a conduit to deliver $\mathrm{CO_2}$ ultimately resulting from soil respiration to the atmosphere.

Acknowledgements. This research is part of the Project "Carbon sequestration and release in lagoons and reservoirs" coordinated by Petrobras Research and Development Center (CENPES), on the person of Bias M. Faria. The authors are grateful to CENPES/PETROBRAS, CNPq, CAPES and FAPERJ for the financial support and scholarships. We thank D. Bastviken, the handling editor Steven Bouillon and both reviewers, J. Downing and the other anonymous, for their valuable comments.

Edited by: S. Bouillon

References

Amado, A. M., Cotner, J. B., Suhett, A. L., Esteves, F. D., Bozelli, R. L., and Farjalla, V. F.: Contrasting interactions mediate dissolved organic matter decomposition in tropical aquatic ecosystems, Aquat. Microb. Ecol., 49, 25–34, 2007.

Archer, C. L. and Jacobson, M. Z.: Evaluation of global wind power, J. Geophys. Res.-Atmos, 110, doi:10.1029/2004jd005462, 2005.

Carmouze, J. P., Knoppers, B., and Vasconcelos, P.: Metabolism of a subtropical brazilian lagoon, Biogeochemistry, 14, 129–148, 1991.

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. and Caraco, N. F.: Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of sf6, Limnol. Oceanogr., 43, 647–656, 1998.

Cole, J. J., Pace, M. L., Carpenter, S. R., and Kitchell, J. F.: Persistence of net heterotrophy in lakes during nutrient addition and food web manipulations, Limnol. Oceanogr., 45, 1718–1730, 2000.

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.

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

Farjalla, V. F., Faria, B. M., and Esteves, F. A.: The relationship between doc and planktonic bacteria in tropical coastal lagoons, Arch. Hydrobiol., 156, 97–119, 2002.

HerreraSilveira, J. A.: Salinity and nutrients in a tropical coastal lagoon with groundwater discharges to the gulf of mexico, Hydrobiologia, 321, 165–176, 1996.

Hopkinson, C. S., Buffam, I., Hobbie, J., Vallino, J., Perdue, M., Eversmeyer, B., Prahl, F., Covert, J., Hodson, R., Moran, M. A., Smith, E., Baross, J., Crump, B., Findlay, S., and Foreman, K.: Terrestrial inputs of organic matter to coastal ecosystems: An intercomparison of chemical characteristics and bioavailability, Biogeochemistry, 43, 211–234, 1998.

INMET: Relatório anual do instituto nacional de meteorologia – 1991, INMET, Rio de Janeiro, 1992.

Jones, J. B. and Mulholland, P. J.: Carbon dioxide variation in a hardwood forest stream: An integrative measure of whole catchment soil respiration, Ecosystems, 1, 183–196, 1998.

Krause-Jensen, D. and Sand-Jensen, K.: Light attenuation and photosynthesis of aquatic plant communities, Limnol. Oceanogr., 43, 396–407, 1998.

Lennon, J. T.: Experimental evidence that terrestrial carbon subsidies increase co2 flux from lake ecosystems, Oecologia, 138, 584–591, 2004.

Marotta, H., Duarte, C. M., Sobek, S., and Enrich-Prast, A.: Large CO_2 disequilibria in tropical lakes, Global Biogeochem. Cy., 23, GB4022, doi:10.1029/2008GB003434, 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(3), 382–392, doi:10.1007/s10021-010-9325-6, 2010.

Pace, M. L., Cole, J. J., Carpenter, S. R., Kitchell, J. F., Hodgson, J. R., Van de Bogert, M. C., Bade, D. L., Kritzberg, E. S., and Bastviken, D.: Whole-lake carbon-13 additions reveal terrestrial support of aquatic food webs, Nature, 427, 240–243, 2004.

Rantakari, M. and Kortelainen, P.: Interannual variation and climatic regulation of the CO_2 emission from large boreal lakes, Glob. Change Biol., 11, 1368–1380, doi:10.1111/j.1365-2486.2005.00982.x, 1354–1013, 2005.

Raymond, P. A. and Cole, J. J.: Increase in the export of alkalinity from north america's largest river, Science, 301, 88–91, 2003.

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, 617–620, 2002.

Schindler, D. W.: Factors regulating phytoplankton production and standing crop in worlds freshwaters, Limnol. Oceanogr., 23, 478–486, 1978.

Sobek, S., Tranvik, L. J., and Cole, J. J.: Temperature independence of carbon dioxide supersaturation in global lakes, Global Biogeochem. Cy., 19 1–10, 2005.

Staehr, P. A. and Sand-Jensen, K.: Temporal dynamics and regulation of lake metabolism, Limnol. Oceanogr., 52, 108–120, 2007.

Suzuki, M. S., Ovalle, A. R. C., and Pereira, E. A.: Effects of sand bar openings on some limnological variables in a hypertrophic tropical coastal lagoon of brazil, Hydrobiologia, 368, 111–122, 1998.

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.

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

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