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Increased nocturnal CO_2 concentration during breeze circulation events in a tropical reservoir

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ABSTRACT

The Balbina reservoir (59°28'50" W, 1°53'25" S), located near the city of Manaus, AM in central Amazonia, is the second largest hydroelectric reservoir in the Amazon basin. Carbon dioxide concentration measurements were performed at high frequency (10 Hz) at this reservoir with an IRGA Model LiCOR 7500A and meteorological variables were measured with a floating platform with sensors 2 meters above the surface of the lake. Maximum and minimum CO_2 concentrations were observed during the night, related to forest breeze enriched with CO_2 and the respiration or photosynthetic activity of the lake. Due to the dimensions of the lake, both land and lake breezes control the concentration of CO_2. CO_2 showed a strong correlation with the meteorological variables, temperature (- 0.76) and relative humidity (0.71). However, only the wind direction showed a statistically significant effect at 5% in the cross-correlation. Our results corroborate other studies in this lake and other Amazonian reservoirs.

Keywords: breeze, meteorological variables, wind direction.

Aumento da concentração noturna de CO_2 durante eventos de circulação de brisa em um reservatório tropical

RESUMO

O reservatório de Balbina (59°28'50" W, 53°1'25" S), localizado próximo à cidade de Manaus - Amazonas na Amazônia central, é o segundo maior reservatório hidroelétrico localizado na bacia Amazônica. Neste reservatório, foram realizadas medidas da concentração de dióxido de carbono em alta frequência (10 Hz) com um IRGA modelo LiCOR – 7500A e variáveis meteorológicas com uma plataforma flutuante com sensores localizados a 2 m da superfície do lago. O máximo (mínimo) da concentração de CO_2 foi observado durante a noite (tarde) relacionados a brisa de floresta enriquecida com CO_2 e a respiração do lago (atividade fotossintética). Devido as dimensões do lago, tanto a brisa de lago quanto a terrestre controlam a concentração de CO_2. O CO_2 apresentou uma forte correlação com as variáveis meteorológicas, temperatura (-0.76) e umidade relativa (0.71). No entanto, apenas a direção do vento apresentou significância estatística em 5% no teste de correlação cruzada. Nossos resultados estão de acordo com outros estudos realizados neste lago e em outros reservatórios amazônicos.

Palavras-chave: brisa, direção do vento, variáveis meteorológicas.

1. INTRODUCTION

Like the oceans, inland waters play a key role in the regional and global carbon cycle (Cole et al., 2007; Richey et al., 2002; Battin et al., 2008; Raymond et al., 2013). In the Amazon, the efflux of CO_2 from inland waters is comparable to the carbon stored in Amazonian forest' trees (Phillips et al., 1998) and much larger than the carbon exported by the Amazon to the oceans (Richey et al., 2002). More recently, reservoir lakes, particularly in the tropics, have been identified as sources of CO_2 and CH_4 into the atmosphere (Galy-Lacaux et al., 1999; Guérin et al., 2006; 2007; Kemenes et al., 2007; 2011). The transport and dispersion of gases are frequently and greatly affected by local wind systems such as breezes (Moura et al., 2004; Biermann et al., 2013; Manesh et al., 2014; Wentworth et al., 2015).

Due to the thermal inertia of large bodies of water, the lakes heat and cool more slowly than the adjacent terrestrial surface. On days with little cloud cover, solar radiation warms the earth's surface faster than the surface of the lakes and a temperature difference develops between the surface of the lake and the terrestrial surface. This difference in temperature between the surfaces results in a difference in the temperature of the atmosphere above, which results in a slight disturbance in the pressure field. The wind profile response to the influence of temperature fluctuations on the atmospheric pressure leads to an increase in the gas flux of the lake to the lake edges at low atmospheric levels, and from the edges to the center of the lake at high atmospheric levels. At a certain distance from the continent, the edge flow at the lower levels of the atmosphere rises and returns toward the lake as part of the lake flow at high levels, forming the front of the lake breeze (Simpson et al., 1977).

The effects of breeze circulation on air quality have been investigated for different types of locations with different types of topography and weather conditions. For example, Hastie et al. (1999) identified through meteorological measurements and satellite images that the increase in ozone concentration in Southern Ontario is related to the arrival of the breeze front from Lake Ontario. Hayden et al. (2007) identified that lake breeze circulations are important in the dynamics of SO_4^{2-} formation and secondary organic aerosol in the southwest region of Ontario. Sun et al. (1998) investigated the transport of carbon dioxide, water vapor and ozone through turbulence and local circulation and found that the nocturnal breeze plays an important role in the regional balance of CO_2 in the lake region. Few studies on breeze circulation have been conducted in the Amazon region. Moura et al. (2004) observed the presence of a breeze on the lake of the Balbina reservoir and its influence on the increase of the concentration of ozone when the breeze is from the lake, even when it is nocturnal.

The Amazonian rivers, also develop breeze circulations due to their size. Fitzjarrald et al. (2008) investigated the influence of the breeze circulation of the Amazon and Tapajós Rivers on the rainfall data of the stations located near the confluence of the two rivers east of the Amazon Basin. According to the study, the breeze circulation of the Amazon River affects rainfall more than the breeze of the Tapajós River, which moves contrary to the prevailing wind. For this same region, Lu et al. (2005) investigated mesoscale circulations and atmospheric CO_2 variations over a heterogeneous landscape of forests, pastures, and large rivers (Amazon and Tapajós Rivers). The results found by Lu et al. (2005) suggested that the topography, the differences in roughness, length between water and land, the ‘‘T’’ shape juxtaposition of Amazon and Tapajós Rivers, and the resulting horizontal and vertical wind shears all facilitated the generation of local mesoscale circulations. The Santarém region had already been characterized by Silva Dias et al. (2004) with a shallow diurnal river breeze circulation forced by differential heating between the forest and the Tapajós and Amazon Rivers during trade winds breaks.

Breeze circulations are also influenced by terrain topography (Sun et al., 1998; Eugster and Siegrist 2000; Lu et al., 2005; Tóta et al., 2012). Eugster and Siegrist (2000) investigated the influence of the nocturnal advection of CO_2 on CO_2 flow measurements over a plateau area between two mountains. The study revealed that during the early evening, when the energy balance becomes negative, the flow of CO_2-rich cold air begins to be advected along the river valleys. During the first half of the night, the CO_2-rich air layer increased in depth reaching its maximum depth just after midnight and remained relatively constant until dawn. The CO_2 advected from the forest to the lake added to the lake's respiration, and led to a nocturnal CO_2 peak. After dawn, the vertical profile of CO_2 was again well mixed. Nicholls et al. (2004) study conducted in the Great Lakes region (Wisconsin, USA) showed that a large diurnal cycle of CO_2 concentration over the lakes appeared to be mainly due to the combined action of katabatic winds, ambient winds, and the lake breeze circulation. These results suggest that meteorological processes associated with the complex terrain in this region leads to substantial CO_2 advection. Therefore, meteorological as well as biological processes are likely to be important causes of CO_2 variability in that region.

In the present study, we investigated the diurnal cycle of CO_2 concentration on the surface layer just above the surface of the water with a high frequency sensor and measured some meteorological variables such as wind, temperature, precipitation and relative humidity. By means of the measurements we identified the presence of a breeze over the reservoir lake and through statistical tests we related its effect with the increase of the CO_2 concentration on the lake in the nocturnal period. We also compare our results with other studies of reservoirs and lakes.

2. MATERIAL AND METHODS

The Balbina Hydroelectric Power Plant was built in Central Amazonia in 1987, on the Uatumã River, located in the city of Presidente Figueiredo, 155 km north of Manaus, AM. The Balbina Reservoir (Figure 1) is the second largest hydroelectric reservoir located in the Amazon (59°28'50" W, 1°53'25 "S) with an average flooded area of 1770 km^2, an average depth of 10m and time of residence of approximately 12 months (Kemenes et al., 2007; 2011). The climatology shows the maximum of the rainy season in the months of March, April and May and the dry season in the months of August and September.

The field experiment was carried out between July 15 and 20, 2013, during the transition season (rainy to dry). Meteorological data on wind, temperature, relative humidity and precipitation were collected through a floating structure anchored in the main channel of the reservoir lake. The data used for CO_2 concentration analysis (for 32 hours) were collected on July 18 and 19 using an infrared gas analyzer (IRGA) (Li-7500 A, Li-Cor, USA) with 10 Hz. The concentration data were analyzed with an average of 5 minutes and related to meteorological data measured by the floating structure.

A floating structure was instrumented with a HOBO U-30 station with telemetric operation via GSM technology, whose data were sent to the HOBOlink server of the Amazonas Climate Change Network, under the responsibility of the State University of Amazonas (Remclam / UEA). The structure was in operation throughout the campaign with a height of 2 m between the sensors and the water surface. The meteorological variables obtained by the floating structure were sampled every 5 minutes and for the precipitation the hourly accumulation was calculated.

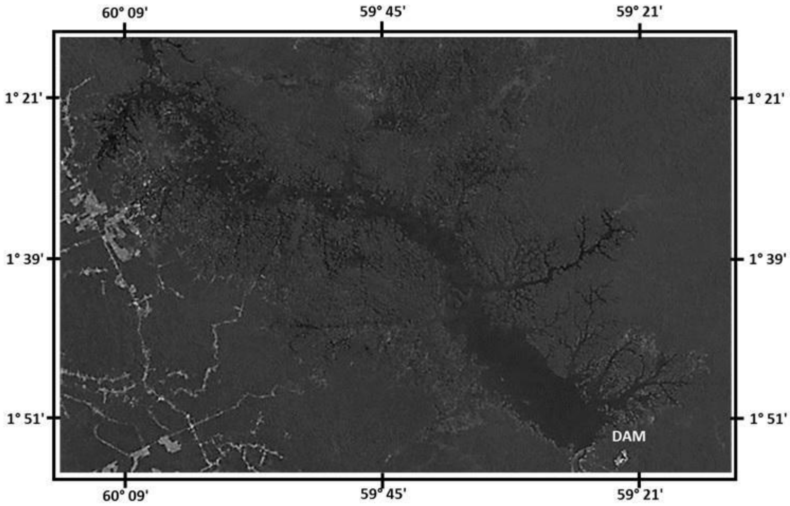

Figure 1. Location of the dam of the Balbina Hydroelectric Power Plant, in the municipality of Presidente Figueiredo - AM at 192 km from Manaus.

The wind speed measurements were adjusted to 10 m above the water surface (U_{10}) according to Amorocho and DeVries (1980) (Equation 1).

$$U_z = U_{10}\left[1 - C_{10}^{0,5}\kappa^{-1}ln(10/z)\right] \quad (1)$$

Where: C_{10} = surface drag coefficient for wind at 10 m (0.013, Stauffer, 1980); κ = von Karman's constant (0.41); z = height of the wind speed measurement above the water surface.

For the analysis of the data, we used the statistical methods of Pearson's linear correlation and the function of cross correlation. Pearson's linear correlation proposes to verify the degree of association between two or more variables and the cross-correlation function is a measure of similarity between two signs of two variables as a function of a delay applied to one of them, that is, it determines if the two processes are correlated (Vandaele, 1983). In this study, we verified the direct correlation and time lag between CO_2 and meteorological variables (temperature, precipitation, relative humidity, direction and wind speed).

According to Chatfield (2013), the cross-correlation function estimator is given by the formula (Equation 2):

$$\hat{\rho}_{xy}(h) = \frac{\sum_{t-1}^{n-h}(x_{t+h}-\bar{x})(y_t-\bar{y})}{n^{-1}\sum_{t-1}^{n}(x_t-\bar{x})^2\sum_{t-1}^{n}(y_t-\bar{y})^2} \quad (2)$$

Where: x_t e y_t = time series; $\underline{x}$ e $\underline{y}$ = averages; h = lag coefficient between the series; n = number of observations. When working with counting we used autocorrelated data, and to avoid erroneous interpretations in the detection of cross-correlation, we used the technique of pre-bleaching, which is a process to remove unwanted autocorrelations before the analysis of interest.

3. RESULTS AND DISCUSSION

The daytime variation of the CO_2 concentration is shown in Figure 2. The peak occurs around 7 h due to the accumulation of CO_2 concentration before dawn. As the day progresses, the CO_2 concentration decreases gradually and reaches a minimum (377.14 ppm) at around

17 h due to high atmospheric mixing and increased photosynthetic activity (Imberger, 1985; Wofsy et al., 1988; Mahesh et al., 2014). After sunset, the concentration increases, with the maximum peak (476.52 ppm) around 18 h due to the absence of photosynthetic activity and breeze circulation, which will be discussed later. The gray area of Figure 2 highlights the accumulation of CO_2 concentration for the nighttime, the equation for which has an angular coefficient of 0.53 for a sampling time of 5 minutes, which yields a rate of CO_2 concentration of 6.36 ppm.h^{-1}. This rate represents a difference in concentration between the two periods which amounts to approximately 100 ppm. During the night, surface radiative cooling provides a thermodynamically stable layer, and its temperature inversion leads to a decrease or absence of mixing and consequently to the accumulation of CO_2 concentration on the surface of the lake. Diurnal variations were also observed in the studies of Moura et al. (2004) for ozone by Mahesh et al. (2014) for CO_2 and Harris and Kotamarthi (2005) in the transport of pollutants.

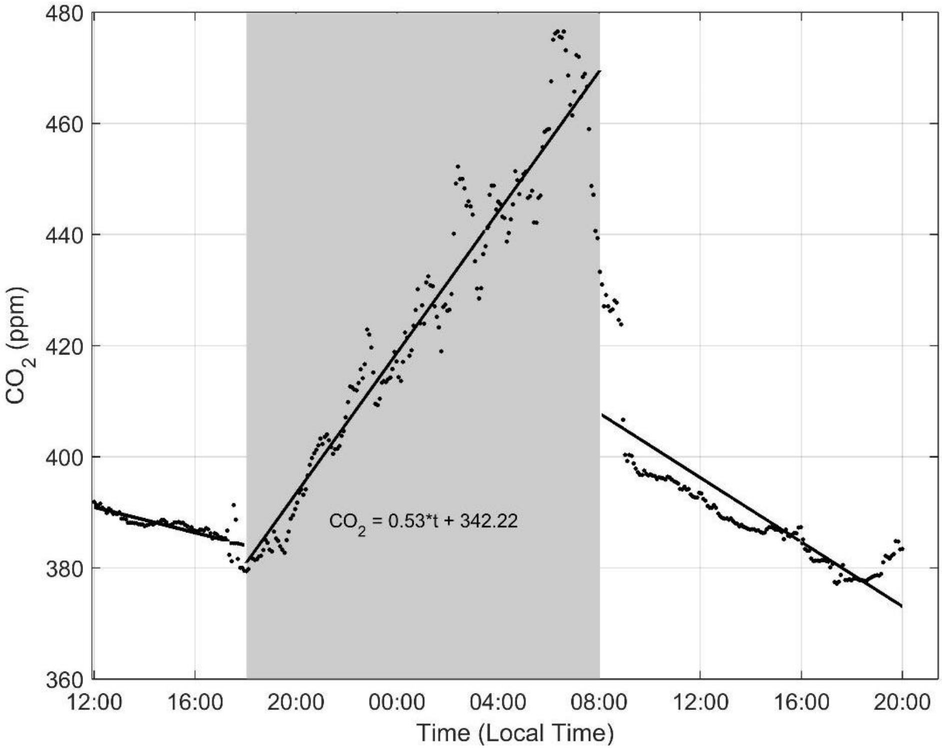

Figure 2. Concentration of CO_2 with 10 Hz sampling and average of 5 minutes, during 32 hours, on the lake of the reservoir of Balbina - AM. Continuous lines indicate the trend of concentration for the day and night period.

The CO_2 flux depends mainly on the concentration gradient between the water surface and the air and the physical transfer or turbulent energy at this interface (MacIntyre et al., 1995). Forests act as a source of CO_2 at night (respiration) and as a sink during the day (photosynthesis). In turn, lakes are continuous sources of CO_2 discharges into the atmosphere (Richey et al., 1987). Thus, the increase in CO_2 concentration on the surface of the lake at night is expected and occurs due to respiration and the decrease or absence of turbulence, since in lakes the dominant source of turbulence on the surface of the aqueous boundary layer is wind-controlled (Cole and Caraco, 1998). However, other physical factors should play a role in increasing the concentration, since this nocturnal increase represents ~ 33% of the daytime concentration.

Figure 3 shows the meteorological variables during the field experiment. The wind, for the night period from 18h on the 18th to 6h on the 19th, showed values of 0.3 - 3 m s^{-1}. Figure 3 shows that up to 16h the wind is predominantly from the west and at 16h it changes to the northeast, which characterizes the lake and forest breezes, respectively, wherein the lake breeze occurs during the day and the forest breeze at night. We also noticed that the relative humidity presents a well-defined cycle for this same time at 16h, with a maximum close to 00h. During the campaign the formation of fog was observed on the surface of the lake after sunset (18h) which is justified by the high values of relative humidity, approximately 100%. In very low wind conditions (< 3 m.s^{-1}) or with the absence of winds, the CO_2 exchange in the lake can be controlled mainly by convective movements caused by the loss of heat that occurs, for example, when the surface of the water is warmer than the air just above (MacIntyre et al., 1995).

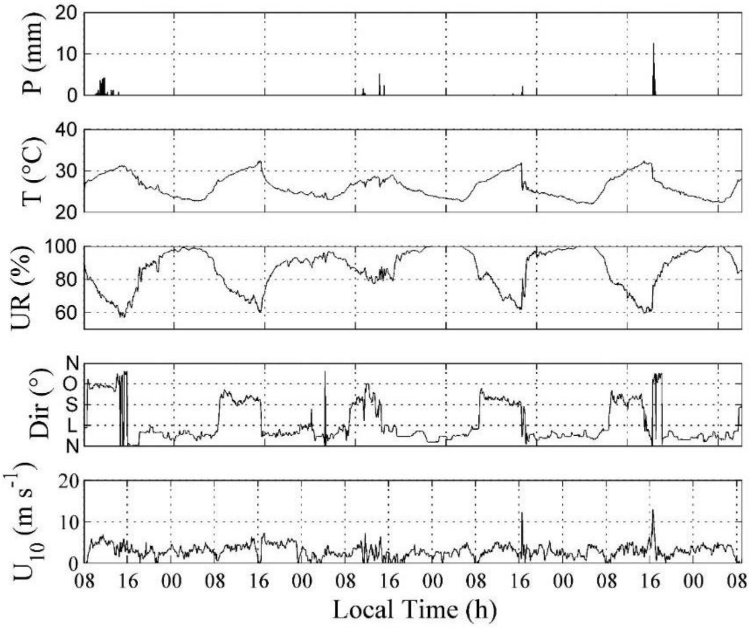

Figure 3. Meteorological variables, precipitation (mm), temperature (°C), relative humidity (%), wind direction (°) and speed normalized (10 m s^{-1}) measured using an instrumented platform with a HOBO U -30 weather station to send data via GSM to the base of Remclam / UEA Manaus- AM.

The Pearson correlation (r) was calculated between CO_2 and each meteorological variable. According to Amorin (2013), the classification of Pearson's correlation values is considered to be weak ($0 \leq r < 0.39$), moderate ($0.40 \leq r \leq 0.69$), strong ($0.70 \leq r \leq 1$). In this study, there was a weak correlation between CO_2 and wind velocity (- 0.20), moderate with atmospheric pressure (0.48) and wind direction (- 0.55) and strong with air temperature (- 0.76) and relative humidity (0.71) (Table 1).

The Pearson correlation detected an inversely proportional (strong and statistically significant) relationship between temperature and CO_2. This relationship was also found by Hensen et al. (1996) and Silva Junior et al. (2004). The high values of air temperature occur at the moment when the concentration of CO_2 presents its minimum values, and there is an inverse relationship between both variables. After sunset, there is release of CO_2 into the atmosphere, not instantaneously, but during the night period, due to the absence of sunlight, in addition to the natural increase of the relative humidity of the air and decrease of its temperature, which stimulates not only greater respiration of roots, but also of the microorganisms responsible for the decomposition of organic material. This nocturnal emission can represent more than 80% of all CO_2 emitted by the ecosystem (Meir et al., 1996). Obviously, this is all associated with an intense decrease in nocturnal atmospheric turbulence to produce a greater dispersion of the nocturnal values in relation to the diurnal values. The direct association between the relative humidity of the air is probably due to the fact that it has a cycle similar to that of the concentration of CO_2, where the daily cycles are very similar with respect to the maximum and minimum values, generating an increase of the atmospheric stability and a decrease of the dispersion of CO_2.

Table 1. Linear Pearson correlation between CO_2 and meteorological variables.

Variables	**Correlation**	**p-valor**	**Confidence Interval**
Air temperature	-0.76	< 0.05	-0.80 to -0.72
Relative humidity	0.71	< 0.05	0.66 to 0.76
Precipitation	-0.12	0.024	-0.21 to -0.02
Wind direction	-0.55	< 0.05	-0.62 to -0.48
Wind velocity	-0.20	< 0.05	-0.29 to -0.10

5% significance.

From the cross-correlation analysis, statistical significance was observed between CO_2 and wind direction and velocity, lag 5 and 18, respectively. That is, the correlation between the variables occurs with lags of 5 and 18 minutes. In addition to the direct correlation detected in the Pearson linear correlation, there was a lagged effect of direction and wind velocity with CO_2 concentration. The cross-correlation function was used after pre-bleaching to eliminate deterministic or stochastic trend structures present in a time series. Thus, when calculating the autocorrelation between two variables, it will not be influenced by this structure (Box et al., 2015). In this case, double pre-bleaching was used, where it is adjusted for each variable of its own integrated autoregressive moving average model (ARIMA). This method is considered more robust because the two series become white noise and the correlation between them can be purely due to chance. This makes it evident that even from a small sample of data it is possible to verify statistical significance between the variables under study, signaling the existence of the strong possibility of the relation of the breeze effect on the CO_2 concentration in the Balbina, AM reservoir.

To study the influence of forest and lake breezes on CO_2 concentration, we considered all winds from 0° - 180° as a forest breeze and those coming from 180° - 360° as lake breezes. The characterization of CO_2 from lake or forest is shown in Figure 4. About 58% of the winds are forest and occur at night. Although water bodies act as a source of CO_2, the amount of CO_2 concentration in lakes is lower than that of forest (Wofsy et al., 1988; Richey et al., 2002). The other 42% are lake breezes occurring during the daytime period. Moura et al. (2004) found an increase in the ozone concentration of ~ 22% and a decrease of ~ 60% in relation to the daily average due to the presence of lake and forest breezes, respectively. In this study the nocturnal concentration represents ~ 33% of the daytime concentration, which is strong evidence of the influence of the breeze on the concentration of CO_2, since the concentrations of ozone and carbon dioxide are negatively correlated (Wofsy et al., 1988). Thus, the forest breeze possibly influences the concentration of nocturnal CO_2 over the lake.

The lake of the Balbina reservoir has a large enough area to establish a breeze regime (Moura et al., 2004). According to Moura et al. (2004), the lake and forest breezes are present in a well-defined way, the lake breeze being best characterized between 10 to 14h, while the forest breeze is evident between 16 to 08h. Tóta et al. (2012) identified local circulation over a dense forest in Manaus, AM with moderately complex terrain and verified the existence of a drainage runoff in slope and valley areas and that horizontal and vertical CO_2 gradients are modulated by these circulations within the forest. The forest breeze is rich in CO_2 due to the forest respiring at night, creating a gradient between the forest canopy and the surface of the lake, favoring the flow of CO_2 towards the lake at night and justifying the increase in concentration. Sun et al. (1998) showed that a lake breeze can generate significant transport of CO_2 by advection. The study also revealed that a lake in the center of a forest region would act as a CO_2 chimney and thus create a mesoscale circulation that generates significant advection in the forest around the lake.

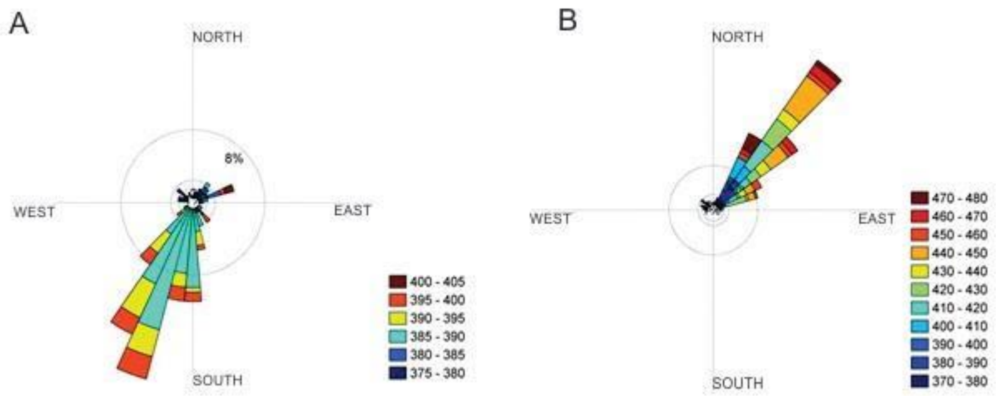

Figure 4. Evidence of the breeze effect on CO_2 concentration in Lake Balbina A) wind direction versus concentration of diurnal CO_2 (lake breeze) and B) direction of the wind versus concentration of nocturnal CO_2 (forest breeze).

Since different physical, chemical and biological processes, regulate CO_2 exchange across the water-air interface, it is expected that these processes exert varying levels of controls on different time scales, leading to temporal variations in CO_2 emission rates. Temporally discrete field samplings of pCO_2 and atmospheric CO_2 concentrations for estimating CO_2 emission rates are usually conducted during the daytime when fair weather conditions predominate, and these emission rates are then temporally up-scaled to obtain annual emission rates (Cole et al., 2007; Raymond et al., 2013). Not only local and mesoscale events influence the concentration of CO_2 in reservoirs. Studies by Liu et al. (2016) revealed that during the presence of synoptic events the emission of nocturnal CO_2 over a reservoir on the Mississippi river increased approximately 70% in relation to daytime emissions. Concentration gradient measurements are typically collected during the day and in ideal weather conditions. Thus, the omission of nocturnal CO_2 concentration and flux data leads to an underestimation of emissions. Eugster and Siegrist (1999), Eugster et al. (2003) and Vesala et al. (2006) had problems with the contamination of the CO_2 advected by the surrounding terrain on the surface of the lake where eddy covariance measurements were made. The solution that was tried by the authors was to reduce the eddy covariance averaging time from 30 minutes to 5 minutes.

4. CONCLUSION

In situ measurements of CO_2 concentration were performed on the lake of the Balbina, AM hydroelectric power plant with a high frequency sensor and averages were calculated every 5 minutes and meteorological variables were recorded with an HOBO - U30 weather station in the same time interval. The maximum CO_2 concentration was 476.52 ppm before dawn and a minimum of 377.14 ppm before nightfall. There was a strong correlation between CO_2 and air temperature (- 0.76) and relative humidity (0.71), but only the direction of the wind presented statistical significance (5%) with CO_2, which proves the seasonal relationship of wind direction with CO_2. Although the CO_2 concentration data only show the daily cycle for a specific day, we believe: 1) that this pattern will be repeated throughout the annual cycle, since the breeze circulation has already been identified for this lake in the study by Moura et al. (2004), and in this study it was configured during the five days of measurement; 2) The daily CO_2 cycle on lake is also known and reveals this accumulation in the night period; 3) Other studies reveal that other factors, in addition to biological and chemical factors, interfere with the dynamics of CO_2 on lakes; 4) The circulation of breezes on the Balbina lake contributes to the an increase of the nocturnal concentration of CO_2 on the lake due to the advection of the air coming from the adjacent forest enriched with CO_2 due to the respiration of the soil and the vegetation. This study also suggests that a long-term investigation to capture the seasonal effects of the region and the estimation of the lake respiration rate are essential for the closure of the CO_2 balance and to define with precision the contribution of the forest breeze to the concentration of CO_2 over the lake. The data, although preliminary, provides evidence of the influence of the circulation of a forest breeze on the effect of the increase of nocturnal CO_2 concentration on the lake of Balbina, AM.

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