XXIII SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

CHANGES IN THE SEASONAL FLOOD DURATION OF LAGO GRANDE DO CURUAI IN RESPONSE TO THE DROUGHTS OF 2005, 2010 AND 2016

Edson Filisbino Freire da Silva [1] ; Daniel Andrade Maciel [2]; Daiane Vieira Vaz [3]; Katia Maria Teixeira Ferreira [4]; Evlyn Marcia Leão de Moraes Novo [5]

RESUMO – O objetivo deste estudo foi analisar as mudanças na duração da inundação sazonal no Lago Grande do Curuai, em resposta às secas extremas que ocorreram nas últimas duas décadas. O sensor Aqua MODIS foi utilizado para mapear a permanência das águas abertas (aqui chamado de duração da inundação), entre os anos de 2002 e 2017. As reflectâncias de superfície das bandas 4 (555 nm) e 5 (1240 nm) do produto composto por 8 dias de imageamento foram utilizadas para calcular o Normalized Difference Water Index (NDWI), o qual foi utilizado para separar áreas “inundadas” de “não-inundadas”. Posteriormente, a percentagem de tempo de inundação (% ano^{-1}) de cada pixel por ano foi calculada. Os resultados mostram que nos anos de seca extrema (2005, 2010, e 2016) a duração da inundação foi menor que nos outros anos. As áreas de água aberta permanente ao longo do ano (lagos perenes) foram as mais afetadas nos anos de seca, tendo sua área reduzida a apenas 38% da área de lagos perenes mapeados em 2014, o qual é considerado um ano de cheia extrema. Os resultados são preliminares, mas mostram a capacidade do sensor MODIS em ser aplicado no monitoramento da inundação na região.

ABSTRACT– The objective of this study was to analyze the seasonal changes in the flood duration in the Curuai Lake, in response to the extreme droughts occurring in the past two decades. The Aqua MODIS sensor was applied to map flood duration impact on open waters of Curuai Lake floodplains, from 2002 to 2017. For that, year-round permanent open water areas were used as a proxy of the duration of inundation, since optical sensors do not allow the detection of water below the forest canopy. The eight-day surface reflectance composition of bands 4 (555 nm) and 5 (1240 nm) were used to calculate the Normalized Difference Water Index (NDWI), which was then applied to distinguish between flooded and non-flooded areas. Furthermore, the flooded time (% yr^{-1}) for each pixel was calculated. The results show that in the drought years (2005, 2010, and 2016) the flooded duration was lower than in the regular years, as expected. The perennial open water surfaces (perennial lakes) were the foremost affected in the drought years, corresponding to only 38% of areas when compared to an extreme flood year (2014). The results are preliminary but show that Aqua MODIS capability for monitoring flood duration in the region.

Palavras-Chave – Sensonriamento-Remoto, Inundação, Amazônia

---

1) Instituto Nacional de Pesquisas Espaciais - INPE, 515, 12227-010, São José dos Campos, Brazil, edson.freirefs@gmail.com.
2) Instituto Nacional de Pesquisas Espaciais - INPE, 515, 12227-010, São José dos Campos, Brazil, damaciel_maciel@hotmail.com.
3) Instituto Nacional de Pesquisas Espaciais - INPE, 515, 12227-010, São José dos Campos, Brazil, daiane.v.vaz@gmail.com.
4) kmtferreira@gmail.com.
5) Instituto Nacional de Pesquisas Espaciais - INPE, 515, 12227-010, São José dos Campos, Brazil, evlyn.novo@inpe.br.

1. INTRODUCTION

The flooded areas in the Curuai Lake (Lago Grande do Curuai) are seasonal and modified by the inflow from the Amazon river, seepage from groundwater systems, rainfall, and runoff. The seasonal flooding is comprised by two periods: the inflow period that starts at the end of November and continues to end of March, and the outflow period that occurs from March to November (Bonnet et al., 2008). In the Curuai Lake, the inflow from the Amazon river accounts for 77% of the total input, followed by rainfall and runoff (10%) and seepage (4%). The Amazon region, where the Curuai Lake is located, has been affected by extreme drought and flood years caused by reduced and intense rainfalls, respectively. These drought/flood years are associated with La Niña, El Niño, and moisture transport anomalies from the tropical Atlantic into Amazonia. Moreover, the drought years have been more frequent in the past two decades (e. g., the drought years of 2005, 2010, and 2016) and may intensify through the 21st century (Marengo and Espinoza, 2016; Panisset et al., 2018).

The inland waters (e. g., Curuai Lake) have a substantial role in the carbon cycle, either global or regional scales. The carbon sources in inland waters, natural and anthropogenic, are estimated in 1.9 Pg C yr^{-1} on a global scale, being further buried in aquatic sediments, delivered to the oceans, and returned to the atmosphere as gas exchange (Cole et al., 2007). The hydrodynamics can influence the fate of carbon in inland waters; for example, Catalán et al. (2016) show that lower water retention time increases organic carbon decay. Explicitly in the Curuai Lake, the outflow exposes shallow areas and favors organic matter mineralization; on the other hand, areas that are often flooded receive more organic matter inputs from the alluvial forest and favors the organic matter sedimentation (Zocatelli et al., 2013).

The extreme events related to drought years may impact the flooded areas of Curuai Lake floodplains, and then alter the organic matter mineralization/sedimentation and the local carbon cycle. For this reason, understand how the Curuai Lake flooded areas respond to those extreme events is very important. Hence, the objective of this study is to investigate the changes in the flood duration of Curuai Lake floodplain using passive remote sensing. First, the Curuai Lake flood duration is mapped for each year, from 2002 to 2017. Last, the changes in flood duration along with the time series and its relationship with the drought/flood years are investigated.

2. MATERIAL AND METHODS

2.1 Study Area

The Curuai Lake floodplain (Figure 1) is located in the Lower Amazon River floodplain, next to the Óbidos city in Pará, Brazil. Numerous interconnected lakes, temporarily or permanently connected to the Amazon River, composes the Curuai Lake floodplains (Barbosa, 2005). The stage of Amazon River varies 6 m annually with a peak in June and a minimum in November. The lakes' flooded area ranges from 850 km² to 2274 km², including the flooded area with vegetation and the open-water, the last corresponding to 65% of the total flooded area (Rudorff et al., 2011).

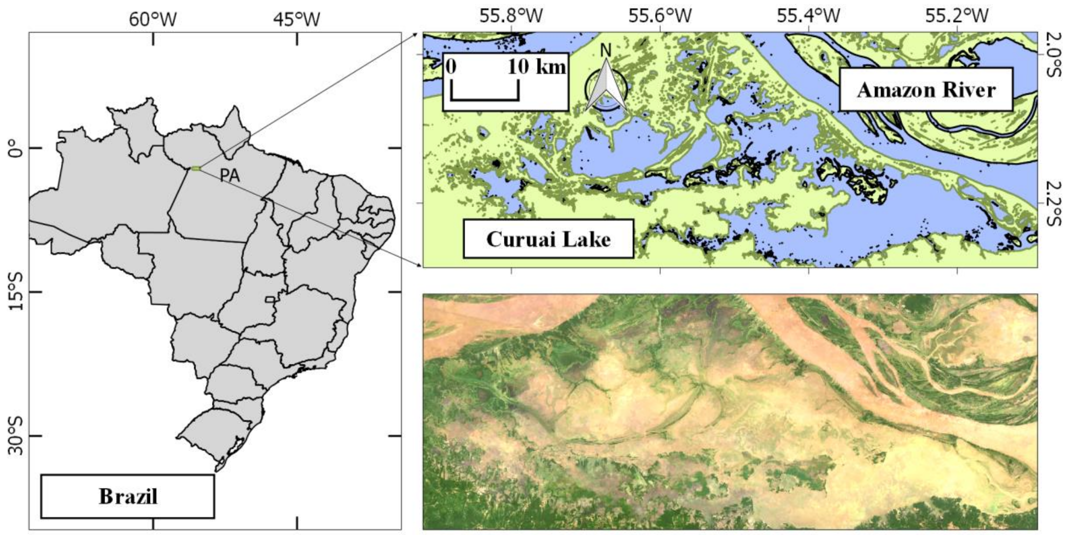

Figure 1 – Study Area – Location of Curuai Lake.

2.2 Image Processing

The MODIS Aqua MYD09A1 product provided by the United States Geological Survey (USGS) was used to map the flood duration. This product provides eight-day composite surface reflectance (SR) images geometrically corrected with a spatial resolution of 500 m from 2002 to 2017. Data assessment and processing was carried out through the Google Earth Engine, a cloud platform and database of remote sensing images with many applications such as deforestation monitoring, natural disasters, and hydric management (Gorelick et al., 2017).

The database consists of an images-cube where each pixel has SR values for each band. In this study, band 4 (555 nm) and band 5 (1240 nm) were utilized. The first step in the processing chain was to mask the interference of the clouds using the layer StateQA to assure that the remaining processed data contained only pixels with the earth's SR. Next, the Normalized Difference Water Index (NDWI) was calculated by the following equation for each eight-day composite image:

$$NDWI = \frac{B_4 - B_2}{B_4 + B_2} \tag{1}$$

where B_4 is the SR of band 4, and B_2 is the R of band 4.

The water baring pixels were identified in NDWI image using a threshold of 0.093, above which all pixels were assumed to have 100% of water with no interference of soil or vegetation (Ji et al., 2009). Furthermore, for each year and pixel, the flooded duration was obtained by the following equation:

$$Flood_{(yr,x,y)} = \frac{p_{flood\ (yr,x,y)}}{p_{total(yr,x,y)}} \times 100\ (\%\ yr^{-1}) \tag{2}$$

where $Flood$ is the flooded duration per year (yr) in the x and y coordinates, the p_{flood} is the number of times that the pixel was classified as flooded based on the NDWI threshold, and the p_{total} is the total number of pixels free of cloud interference used to count p_{flood}.

3. RESULTS AND DISCUSSION

The images were classified in terms of flooded duration for each year. The Curuai Lake floodplain was then split into seven flooded duration classes: lower than 1%, 1 – 20%, 20 – 40%, 40 – 60%, 60 – 80%, 80 – 95%, and above 95%. The > 95% was assumed in this study to be the perennial lakes instead of 100% because we noticed the occurrence of percentages between 97% and 100% in some regions of the Amazon River even during the extreme flood years. The NDWI assumes that SR of water in the green region is higher than that of the short wave infrared (SWIR), accordingly to the threshold used here. However, adjacency effects and extremely high suspended matter concentration increases the reflectance in the SWIR (Knaeps et al., 2012), and reduce the NDWI. In the Curuai Lake, suspended matter concentration can reach up to 1000 mgL^{-1} (Barbosa, 2005), which can contribute to a high signal in SWIR band and classify flooded areas as non-flooded. Therefore, using the Amazon River as a reference, we considered that using >95% of flood duration could represent the perennial areas.

The flood duration of all year presents similarities and also discrepancies in the Curuai Lake floodplain (Figure 2). Considering the similarities, the transition zones to soil and vegetation areas were the areas with the smaller flood duration in all images. On the contrary, there are huge divergences when comparing the years of high water level, called here as flood years (2009, 2012, and 2014) and the years of shallow water level, called here drought years (2005, 2010, and 2016). It is important to highlight that in the literature the year 2016 was not appointed as being a drought year, but the low flood duration depicted by the map suggests may be a result of the anomalous precipitation deficit of 2015 (Panisset et al., 2018).

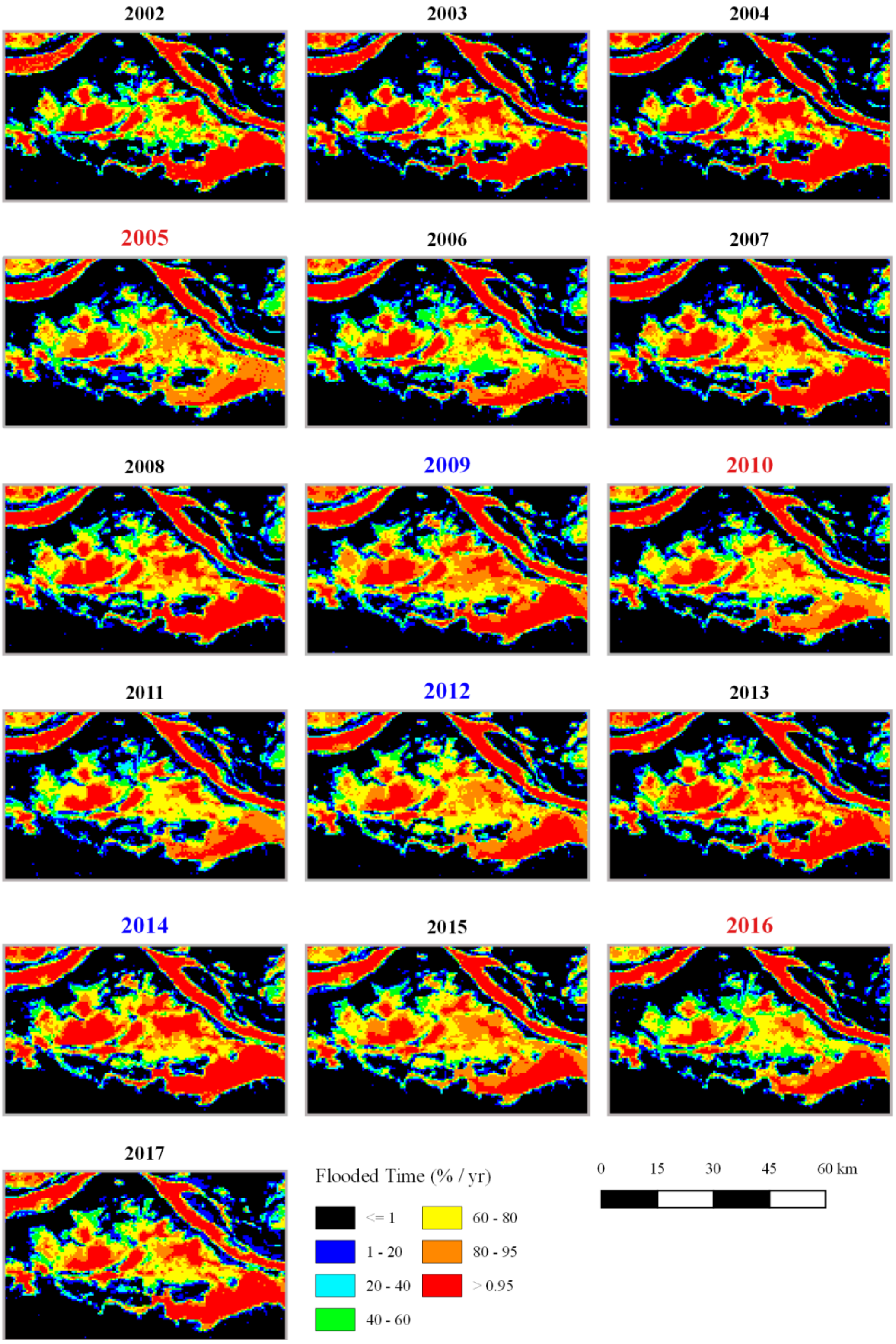

Figure 2 – Flood duration of Curuai Lake. The drought and flood years are highlighted in red and blue titles, respectively.

The perennial lakes in the Curuai Lake floodplain are those undergoing visible changes in the drought years. In those years, the classes occupying the most extensive areas (Table 1) were 80-95 % and 60-80% yr^{-1}. On the other hand, during the flooded years Curuai Lake floodplain is mainly covered by the 95 % yr^{-1}. Even comparing the drought years with the remaining years, the changes in the perennial areas during the drought years are evident.

Table 1 – Percentage coverage of each flooded duration class in the Curuai Lake floodplains.

	1-20% yr^{-1}	20-40% yr^{-1}	40-60% yr^{-1}	60-80% yr^{-1}	80-95% yr^{-1}	>95 % yr^{-1}
2002	11%	9%	15%	20%	12%	31%
2003	15%	8%	8%	19%	15%	35%
2004	15%	8%	9%	17%	13%	38%
2005	15%	8%	12%	22%	29%	14%
2006	15%	10%	16%	22%	19%	18%
2007	14%	8%	9%	21%	19%	30%
2008	14%	8%	11%	22%	15%	30%
2009	14%	8%	10%	19%	24%	25%
2010	14%	9%	12%	30%	22%	14%
2011	18%	10%	13%	26%	17%	16%
2012	12%	7%	10%	28%	23%	18%
2013	14%	8%	10%	19%	20%	28%
2014	13%	7%	9%	21%	16%	33%
2015	13%	8%	10%	25%	26%	18%
2016	14%	9%	17%	26%	17%	17%
2017	15%	8%	11%	24%	15%	26%

For highlighting the flood duration changes throughout the years, the area of each class was computed for each year (Figure 3). The minimum and maximum area of each class was 1-20 (146 km^2, 255 km^2), 20-40 (106 km^2, 146 km^2), 40-60 (109 km^2, 234 km^2), 60-80 (226 km^2, 419 km^2), 80-95 (160 km^2, 415 km^2), and perennial (194 km^2, 510 km^2). The drought years showed a clear pattern in the perennial open water class, where a significant loss of area happened in the years 2005, 2010, and 2016. As observed in the images, the perennial open water area suffered a considerable change in the drought years, shrinking to about to 38% of the area when compared to the flood year 2014. Moreover, the remaining classes did not show any pattern in the drought years, suggesting that perennial areas are the most affected by the drought years.

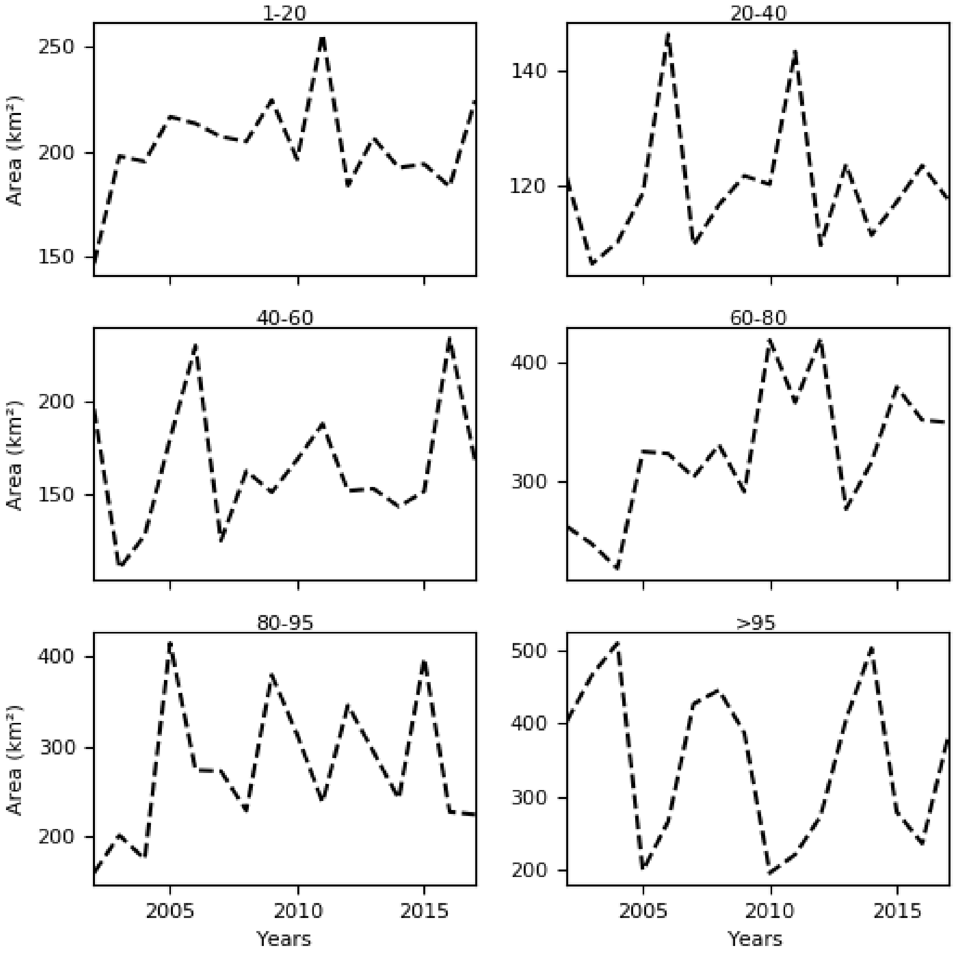

Figure 3 – Time series of flood duration in Curuai Lake, for classes 1 - 20 % yr^{-1}, 20 - 40 % yr^{-1}, 40 - 60 % yr^{-1}, 60 - 80 % yr^{-1}, 80 - 95 % yr^{-1}, and >95 % yr^{-1}.

4. CONCLUSION

The changes in flood duration per year in the Curuai Lake was analyzed using passive remote sensing (Aqua MODIS). Despite the fact that the sensor does not detect flooded areas in regions covered by forest and some types of macrophytes, measuring the flood duration of open waters could provide substantial information about the response of the perennial lakes of Curuai floodplain to extreme drought years, in a long time series (2002 – 2017) of Aqua images. The perennial lakes are the foremost affected in the drought years of 2005, 2010, and 2016, decreasing to about to 38% of the surface occupied in the extreme flood years.

This study is the initial results of further analysis, where the study area will be expanded to other Amazon floodplain lakes. Here, we concluded that the Aqua MODIS can be applied to estimate flood during in the Curuai Lake, and it could be utilized to expand this study.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) - Finance Code 001.

REFERENCES

BARBOSA, C. C. F. (2005). *“Sensoriamento Remoto da Dinâmica da Circulação da Água Do Sistema Planície de Curuai/Rio Amazonas”.* Instituto Nacional de Pesquisas Espaciais (INPE).

BONNET, M. P.; BARROUX, G.; MARTINEZ, J. M.; et al. (2008). *“Floodplain hydrology in an Amazon floodplain lake (Lago Grande de Curuaí)”.* Journal of Hydrology, v. 349, n. 1–2, pp. 18–30.

CATALÁN, N.; MARCÉ, R.; KOTHAWALA, D. N.; TRANVIK, L. J. (2016). *“Organic carbon decomposition rates controlled by water retention time across inland waters”.* Nature Geoscience, v. 9, n. 7, pp. 501–504.

COLE, J. J.; PRAIRIE, Y. T.; CARACO, N. F.; et al. (2007). *“Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget”.* Ecosystems, v. 10, n. 1, pp. 171–184.

GORELICK, N.; HANCHER, M.; DIXON, M.; et al. (2017). *“Google Earth Engine: Planetary-scale geospatial analysis for everyone”.* Remote Sensing of Environment, v. 202, pp. 18–27.

JI, L.; ZHANG, L.; WYLIE, B. (2009). *“Analysis of Dynamic Thresholds for the Normalized Difference Water Index”*. Photogrammetric Engineering & Remote Sensing, v. 75, n. 11, pp. 1307–1317.

KNAEPS, E.; DOGLIOTTI, A. I.; RAYMAEKERS, D.; RUDDICK, K.; STERCKX, S. (2012). *“In situ evidence of non-zero reflectance in the OLCI 1020nm band for a turbid estuary”*. Remote Sensing of Environment, v. 120, pp. 133–144.

MARENGO, J. A.; ESPINOZA, J. C. (2016). *“Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts”.* International Journal of Climatology, v. 36, n. 3, pp. 1033–1050.

PANISSET, J. S.; LIBONATI, R.; GOUVEIA, C. M. P.; et al. (2018). *“Contrasting patterns of the extreme drought episodes of 2005, 2010 and 2015 in the Amazon Basin*”. International Journal of Climatology, v. 38, n. 2, pp. 1096–1104.

RUDORFF, C. M.; MELACK, J. M.; MACINTYRE, S.; BARBOSA, C. C. F.; NOVO, E. M. L. M. (2011). *“Seasonal and spatial variability of CO 2 emission from a large floodplain lake in the lower Amazon”.* Journal of Geophysical Research, v. 116, n. G4, pp. G04007.

ZOCATELLI, R.; MOREIRA-TURCQ, P.; BERNARDES, M.; et al. (2013). *“Sedimentary evidence of soil organic matter input to the curuai amazonian floodplain”*. Organic Geochemistry, v. 63, pp. 40–47.