Spatial-Temporal characterization of optical properties of 4 lakes in the Mamirauá Sustainable Development Reserve - AM (MSDR)

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Abstract. The objective of this study is to evaluate spatial and temporal patterns of the optical properties of four floodplain lakes in Mamirauá Sustainable Development Reserve (MSDR) through the integration of *in situ* and laboratory remote sensing data and limnological field data. This study analysed two water phases, receding waters in July/2015, and rising waters in July, August/2016 and March, April/2016. Results indicate that there are great changes on optical and limnological properties in both time and space. During rising waters we observed a higher concentration of inorganic sediments in lakes located near the major tributaries, whereas for the lakes located in the inner rings of the forest there were higher concentration of organic matter. During the receding waters, we found relatively homogeneous conditions for the optical properties. Those changes between the two water phases were also demonstrated with the Remote Sensing Reflectance (Rrs) measured *in situ*, with a higher magnitude during the rising water. Further analysis about the impact of the variability of optical properties on semi-analytical algorithms are under investigation, and will increase our understanding of the use of remote sensing techniques for monitoring Amazon ecosystems.

Keywords: Remote sensing, Bio optical properties,

1. Introduction

The Mamirauá Sustainable Development Reserve (MSDR) is composed by a floodplain built by the interplay of fluvial geomorphological processes acting upon Solimões and Japura River since the holocene (Latrubesse & Franzinelli). Those processes shaped a topography composed of hundreds of paleochannels, which during the flooding season are converted into temporary elongated lakes. Those processes are also responsible for hundreds of small quite perennial lakes and a small number of large lakes whose area can almost double along the hydrological year from the low to the high water season (Affonso, 2012).

The MSDR is also covered by an almost intact seasonally flooded forest, which is a major source of large amounts of organic matter to those lakes. Affonso et al. (2011) have demonstrated that during high water the limnological properties of several lakes are very similar, but at the low water, there are large variability among the lakes depending on their shape and distance from the main rivers.

The periodic flooding changes the proportion of suspended and dissolved component inputs into floodplain aquatic systems and modifies its physical-chemical conditions (Melack & Forsberg, 2001). Besides that, due to sedimentation and particulate matter transport, those systems suffer constant change of their morphometric features (along with limnology and hydrology characteristics) (Junk et al., 1989).

However, there are not many studies regarding the impact of the periodic flooding on the optical properties of lakes. Knowledge of the water optical properties is important for numerous primary productivity studies as well as for supporting the development of remote sensing tools for monitoring aquatic systems of large regions of difficult access (Boss et al., 2007; Giardino et al., 2007). Following this approach, the objective of this work is to characterize the spatial and temporal dynamic of the optical properties of four floodplain lakes in Mamirauá Sustainable Development Reserve.

2. Methods

2.1. Study Area

The study area is located in the MSDR (Figure 1), in Amazon state, it is a floodplain formed by the confluence of Solimões and Japurá rivers. It is situated near the city of Tefé and 600 km away from Manaus. The annual range of the water level is around 10 m, and, during the flood, the channels, lakes and rivers are interconnected, while during the dry, only the main rivers, channels and lakes are still occupied by water (Ayres, 1993; Ramalho et al., 2009, Affonso, 2012).

The flood starts in May and end in July, while the drought goes from September to November. The rising water starts in January and the receding water in September. The flood pulse has a monomodal annual pattern, and the changes in the water level are due to changes in the precipitation in the Andes and Amazon (Junk et al., 1989).

Lake selection was based on its potential for remote sensing analysis (lake size and shape) and accessibility thought the year. The sampling points were selected to include all the changes in the lake water colour. For this study, Bua Bua, Mamirauá, Pirarara and Pantaleão lakes were selected (Figure 1).

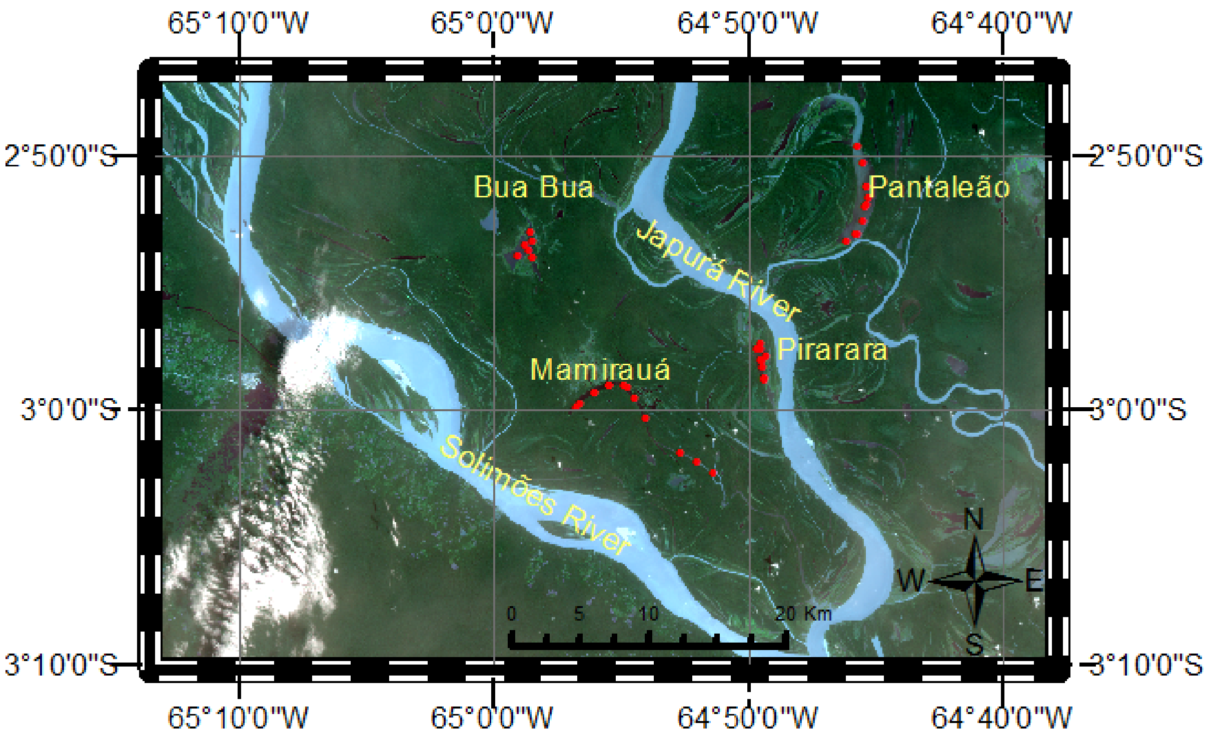

Figure 1. Map of study area and selected lakes inside MSDR. Red circles represent the distributions points per each lake.

2.2. Dataset

Five field missions (M1, M2, M3, M4 and M5) were carried out, missions M2 and M3 during rising water (March and April 2016) and missions M1, M4 and M5during receding water (July/2015, July and August, 2016). For each mission limnological, absorption and radiometric data were collected or measured in each sample station (3 to 6 samples points were visited per lake, with a total of 102 points).

At each sampling station, limnological, optical and radiometric data were obtained. Limnological measurement data included: i) Chlorophyll-a concentration ($\mu g * l^{-1}$) ii) Total Suspended Matter (TSM) and its components Inorganic matter (TSIM) and organic matter (TSOM) fractions ($mg * l^{-1}$), which were analysed according to appropriate methodologies (Wetzel & Likens, 1991).

The absorption coefficient for Phytoplankton, Detritus and CDOM (Coloured Dissolved Organic Matter) was measured following Tassan & Ferrari (2002) and Tiltstone et al. (2002).

The radiometric dataset includes the Remote Sensing Reflectance (Rrs) spectra, measured following Mueller & Fargion (2002). Changes in magnitude and shape were evaluated for each lake and water phase, to assess OACs (Optically Active Component) contribution to the Rrs.

In order to test for differences in the variables as a function of space (each lake) and time (each mission) a two way ANOVA was applied (time and space as factors). The limnological data was analysed using mean and standard deviation values and a ternary plot was used to describe the dominant OAC in four specific wavelengths for each lake and mission (400, 440, 550 and 676 nm). 400 nm was selected because of the high contribution from both detrital and CDOM absorption, 440 nm due to the contribution from all OACs, the 550 nm was selected as a baseline and 676 due to the phytoplankton absorption. The ternary plots are subdivided on 3 groups (mission 1, mission 2 and 3, and mission 4 and 5).

3. Results and Discussion

The results are divided on 3 sub sections: limnological, absorption and radiometric data.

3.1. Limnological Data

Figure 2 presents the mean and standard deviation concentration value of each constituent and each lake along the field campaigns.

Chlorophyll-a, TSM and TSIM concentrations varies independently for both space and time ($p<0.01$, for both factors combined). However, TSOM is homogeneous throughout space, but heterogeneous among missions ($p<0.01$, for time factor).

Chlorophyll-a ranged from 0.2 to 35 $\mu g * l^{-1}$, with minimum value for Pataleão lake during mission 1 and with maximum value for Bua Bua lake. The lowest Chl-a in all lakes occurred during rising water (M1). For TSM, it ranged from 1.6 to 37 $mg * l^{-1}$, with minimum for Bua Bua during M1 and maximum for Pirarara during M2. For TSOM, it ranged from 1.3 to 14.4 $mg * l^{-1}$, with minimum for Bua Bua during M1 and maximum for Pirarara during M3. Lastly, for TSIM, it ranged from 0.2 to 27.6 $mg * l^{-1}$, with minimum for Bua Bua during M1 and maximum for Pirarara during M2.

The higher levels of TSM concentrations in Pirarara and Pantaleão lakes during the rising water (M2 and M3) are mainly caused by the direct input of inorganic matter from major rivers (Solimões and Japurá). These lakes are closer to the Japurá River, than the other two, and have a direct and open channel connection to the main river. Another important aspect is that the forest can act like a net, retaining the composts of higher diameter (detritus) while the smaller ones (CDOM) are carried into the lakes, and may explain the low TSIM concentration on Mamiraua and Bua Bua (Hupp & Noe 2009). Regarding the Chl-a, no clear temporal or spatial pattern

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was identified.

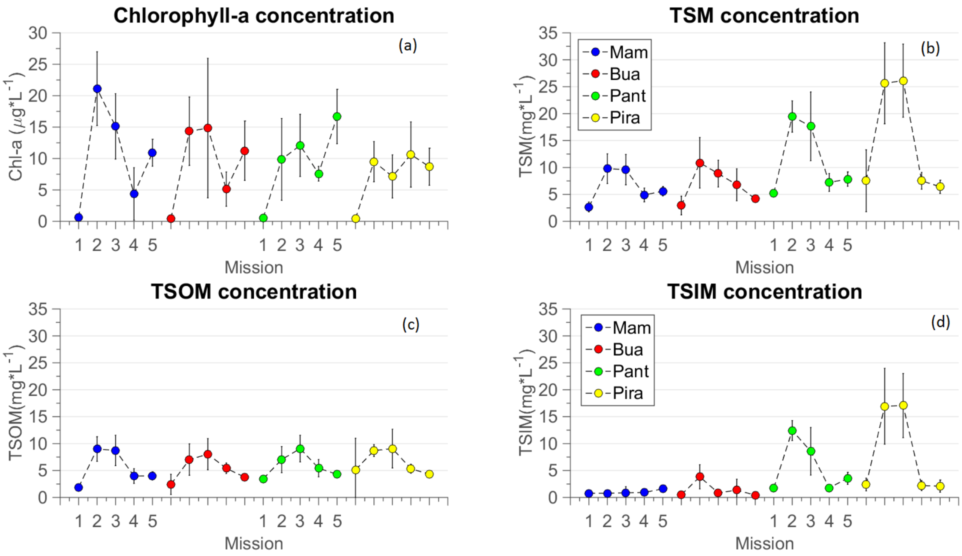

Figure 2. Chlorophyll-a, Total Suspended Matter (TSM), Total Suspended Organic Matter (TSOM) and Total Suspended Inorganic Matter (TSIM) concentrations for all lakes and missions. Plots describe the mean value and standard deviation of all sample points per lake/mission. Lakes are separated by colour and field missions by number (1, 2, 3, 4 and 5). Mamiraua in blue, Bua Bua in red, Pantaleão in green and Pirarara in yellow.

3.2. Absorption data

Two approaches were used to analyse the absorption data: the CDOM absorption spectra and a ternary plot of aCDOM, aPHY and aDET at four wavelengths.

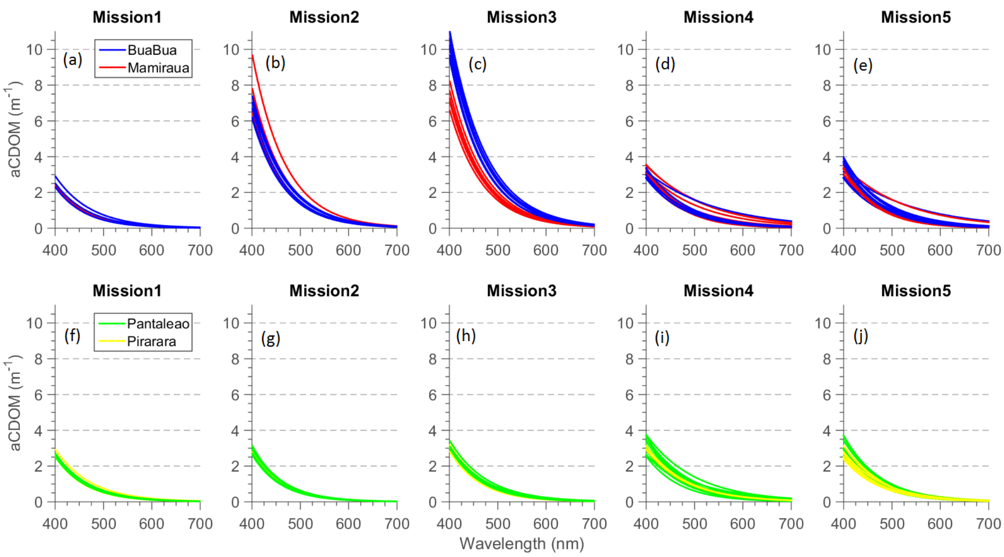

Figure 3. CDOM absorption spectra for each lake and mission. Lakes are identified by colour. Mamiraua in Blue, Bua Bua in red, Pantaleão in green and Pirara in yellow.

All CDOM absorption spectra displayed similar shapes and magnitudes for all lakes at all campaigns (Figure 3), with the exception of Bua Bua and Mamiraua lakes during M2 and M3,

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which was three-fold higher than all remaining campaigns in all lakes. Bua Bua and Mamiraua lakes are located deep in the forest, and during the rising water, a great amount of water reaches the lake through the forest carrying all the accumulated organic matter into them (Gonsior et al., 2016).

ANOVA showed a significant variability for CDOM in both time and space ($p < 0.01$). However, after removing Mamiraua and Bua Bua data, acquired during M2 and M3, from the dataset, no significant differences was observed.

Figure 4 presents the Ternary plot of CDOM, Phytoplankton and Detritus, for four wavelengths (400nm, 440 nm, 550 nm and 676 nm). This analysis shows the dominant OAC in lakes during missions. During receding water (M1, M4 and M5) we observed similar patterns of the OAC contribution to absorption. In general, for 400 and 440 nm, the aCDOM and aDET are contributing with 40% each while aPHY with <20%. For 550 nm there is no dominant OACs, and for 676 nm, aPHY is responsible for >40%, and aDET and aCDOM <40% each. Despite similar contributions, for 676 nm, we can see higher values of aPHY with magnitudes between 60% and 80%, indicating the dominance of aPHY, as expected, since 676 nm is wavelength region of chlorophyll-a absorption.

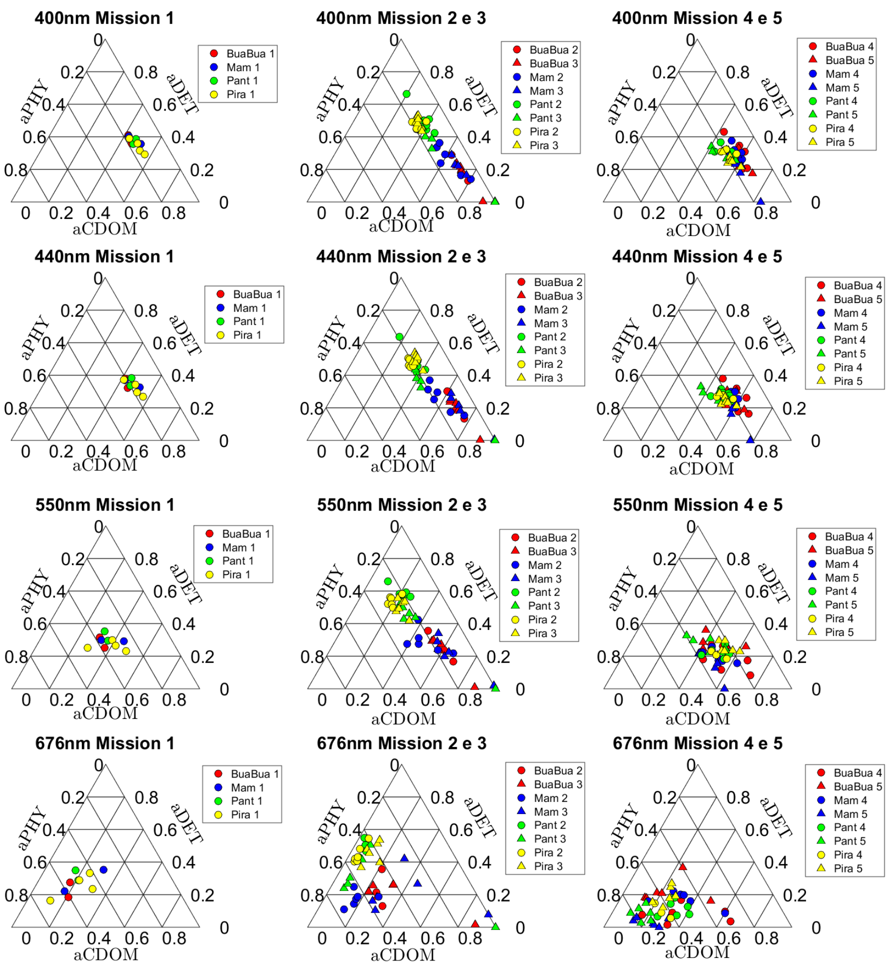

Figure 4. Absorption Ternary for 4 selected wavelengths. Lakes were separated by colour and field missions by number (1 to 5). Mamiraua in blue, Bua Bua in red, Pantaleão in green and Pirarara in yellow.

For M2 and M3, we can observe a distinct OAC absorption pattern among lakes. For 400

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and 440 nm in Pirarara and Pantaleão lakes the aDET contribution is >40%, the aCDOM is <40% and aPHY is < 20%. Compared to M1, M4 and M5, the aDET contribution was higher, reaching values up to 80% for this wavelength. For Mamiraua and Bua Bua, aCDOM is >60%, while aDET is <30% and aPHY is <20% indicating lakes dominated by CDOM absorption. For 550 nm, the contribution pattern was similar to 400 and 440 nm, but with a slightly increase in the aPHY contribution. Lastly, for 676 nm, aPHY is > 40%, aCDOM<40% and aDET<60%, indicating a higher variability in the absorption contribution when compared to M1, M4 and M5. Although 676 nm is usually dominated by aPHY absorption, we observed higher contribution of aDET and aCDOM probably due to its higher concentration values, which was observed *in situ*.

The ternary analysis corroborates our previous results. we identified significant differences for aCDOM and aDET among lakes and missions (space and time), whereas aPHY differences were identify only among lakes (space).

3.3. Radiometric data

Differences in magnitude were observed in Rrs spectra between water phases, with 2 to 4 times higher during rising water (Figure 5). Pirarara and Pantaleão had two times higher values than Mamiraua and Bua Bua in both phases.

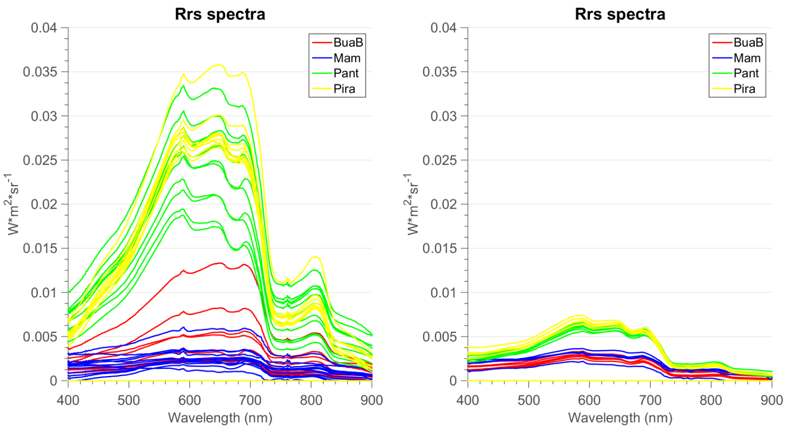

Figure 5. Rrs spectra for each lake. Mission 2 and 3 for the first plot and 1, 4 and 5 for the second plot. The colour represents each lake. Mamiraua in Blue, Bua Bua in red, Pantaleão in green and Pirara in yellow.

The impact of the OACs in the Rrs spectra is evident when examining limnological and absorption data. During the rising water an increase in the TSM concentration was observed in the four lakes, in which explains the increase in Rrs magnitude. In Bua Bua and Mamiraua lakes, an increase in CDOM was observed, which can further reduce the Rrs magnitude. During the receding water, the Rrs magnitude is smaller (bellow 0.01), and two groups can be observed (Mamirauá/Bua Bua, Pirarara/Pantaleão), as seen in the rising water mission.

Another distinguishable feature is the differences in the spectra shape, with a plateau on 600-700 nm for Pirarara, and Bua Bua, and a peak on 600 nm for Pantaleão on Figure 5a. For Figure 5b similar patterns were observed, with a peak near 580 nm for all spectra. Although Mamiraua and Bua Bua are usually grouped because of similar features, in Figure 5a there are more variability in Rrs spectra from Bua Bua lake, probably due to more optical diversity on sampling points.

Those spectra corroborate the results identified in this work, showing that there are differences through time and space for the MSDR.

4. Conclusions

For lakes located near the major rivers, higher TSIM concentration was found during the rising water, while for lakes located deep inside the forest, an increase in CDOM absorption was detected. During the receding water, little differences between the lakes were observed, with relatively homogeneous CDOM absorption, and Chl-a and TSOM concentration. Those changes have direct impact on Rrs spectra, with higher magnitudes during rising waters for all the lakes.

MSDR lakes are an extremely dynamic environment, and the flood pulse cause changes in phytoplankton abundance, sediment and CDOM concentration and composition, further changing the optical properties of water. For longtime monitoring programs in isolated areas, remote sensing techniques can be a crucial tool, enabling aquistion of optical data in real time. To enhance the coherence between remote sensing and *in situ* data in MSDR, algorithms need to be rethought, with emphasis in optically complex inland waters conditions. Future works should focus on reparametrization or development of biooptical algorithms.

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