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GEOSCIENCES

Spatial distribution of atmospheric pollutants and fire outbreaks in the Pantanal biome from 2016 to 2021

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Abstract: Pantanal fires have a significant impact on the environment. Anthropogenic emissions of residual gases have changed the tropospheric composition in this region due to burning. This study aims to analyze the spatial patterns of atmospheric pollutants (including carbon monoxide (CO), nitrogen dioxide (NO_2), black carbon (BC), organic carbon (OC) and sulfur dioxide (SO_2) and aerosol optical depth, along with fire outbreaks across the Pantanal biome from 2016 to 2021. The data collected is based on remote sensing data. The fire outbreaks peaked pollutant concentrations reached their highest between June to November, particularly during the drier months of August to October. This increase was even greater during the last three years (2019-2021), especially in 2020, when the average CO, NO_2, SO_2, BC, and OC concentrations increased by 29%, 31%, 50%, 52%, and 50%, respectively. The rainfall values do not justify the increase in the number of fire outbreaks between 2019 and 2021, indicating that the rise is likely due to increased burning. In 2021, the average monthly rainfall was 48% greater than that in 2016-2020 but it had the highest FRP value and the second highest fire outbreak number and pollutant concentration. The 2020 year experienced a record number of fire outbreaks and the highest levels of pollutants in the atmosphere in the region for this period.

Key words: atmospheric pollution, burning, fire radiative power, Pantanal.

INTRODUCTION

In recent decades, burning areas have increased in Brazil due to the occupation of territories for monoculture planting and livestock farming, causing biodiversity loss, increasing greenhouse effects, and soil fertility loss, in addition to air pollution, which affects the occurrence of respiratory diseases (Granemann & Carneiro 2009). Residual mineral constituents from fuel burning change the atmosphere and soil chemistry, which consequently affects the availability of nutrients for plants (Lemes et al. 2014).

Fire is a natural element of the environment that can positively or negatively impact ecosystems. Forest fires can have negative socioeconomic and environmental impacts, while controlled burns can have several benefits (Pereira et al. 2021). According to Whelan (1995), many fires have natural causes and can be ecologically understood as one of the many factors that act on ecosystems; however, in most regions of the world, the main sources of ignition are associated with human action.

Atmosphere chemical composition changes related to air quality are increasingly concerning. Populations of both urban centers and fire-prone rural areas face a growing number of days in which air quality exceeds the safe limits recommended by the World Health Organization (WHO) and is preconized by the local environmental legislation.

Among the pollutants with the greatest impact on public health are 2.5 µm particulate matter (PM2.5) and tropospheric ozone (O_3). The latter is highly toxic, resulting in effects on human health when inhaled. Unlike most pollutants directly released from sources, O_3 is a secondary pollutant, forming through atmospheric reactions triggered by sunlight. Furthermore, it acts as a significant greenhouse gas, contributing to global warming (Fowler et al. 2008, CETESB 2021, IPCC 2013). Beyond these two pollutants, black carbon (BC), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and organic carbon (OC) affect the environment. High concentrations of these pollutants can negatively impact the environment and human health (Manahan 2009).

In 2019 and 2020, the Pantanal witnessed one of the most devastating wildfires in its recorded history. Changes in the predominant fire regime, such as a greater frequency and intensity of fires, can cause losses of biodiversity, the replacement of native species, and drastic changes in ecological processes (Leal Filho et al. 2021).

The Pantanal is the largest wetland in the world, with a total area varying from 140 km² to 210 km², varying seasonally (Leal Filho et al. 2021). It is mainly located in the Brazilian state of Mato Grosso do Sul, but it extends into Mato Grosso and portions of Bolivia and Paraguay. Its relief is formed by flood plains, accompanied by mountains, hills, and shallow depressions, and it has immense biodiversity (Barros 2006). The region was considered by UNESCO to be a World Natural Heritage Site and Biosphere Reserve (Ferreira et al. 2020).

Approximately 1.1 million people reside in the Brazilian Pantanal, with an additional 16,800 and 8,400 inhabitants in Bolivia and Paraguay, respectively (Leal Filho et al. 2021). These inhabitants depend on a combination of agriculture, fishing, and tourism for their livelihoods. This biome thrives with exceptional biodiversity, harboring over 2 thousand species of plants, 582 species of birds, 41 species of amphibians, 113 species of reptiles, and 132 species of mammals (Leal Filho et al. 2021).

The current forest fire problems seen in the Pantanal are a combination of climate factors and human activities on the plateau and plains (Leal Filho et al. 2021). Many channels, commonly called "mouths", are artificially blocked by farmers to prevent flooding of fields used for pastures (Leal Filho et al. 2021). The fact that water does not spread easily means that fields are not properly irrigated, which in turn increases exposure to drought. Furthermore, inadequate agricultural practices have influenced the water supply to rivers such as Cuiabá and Paraguay, reducing their flow (Leal Filho et al. 2021). This fact also increases vulnerability to droughts.

In 2020, from January to October 10th, 20,926 fire outbreaks were identified in the Pantanal (Santos 2020). It is estimated that in 2020, more than 4 million hectares of the Pantanal were affected by burning, which is equivalent to more than 26.2% of the biome, which covers 15,692,200 hectares in Brazil (Santos 2020). According to Santos (2020), 2,215,000 hectares were in Mato Grosso and 1,902,000, in Mato Grosso do Sul. The greatest impact of the burning is the loss of biodiversity, considering the richness of fauna and flora in this biome. The damage caused by fire and its impacts affects vegetation, animals, the exposed population, and the economy.

Burning is a common practice in Brazil and in the Pantanal region, which aims to clear land with fire to be used to produce agricultural products (slash-and-burn agriculture) or to be used as pasture for animal husbandry. This is a very traditional technique in rural regions of Brazil, and its practice causes a high number of hotspots, as shown in Figure 1, which compares the number of hot spots in Brazil with other countries in South America.

It is important to emphasize that fire and burning are not synonymous. Fire refers to the combustion of a region in an uncontrolled manner and is caused by a natural reason or by human action, whereas burning refers to a controlled way of setting a fire that started due to human action.

Burning is the result of increasing pressure from the human population in these areas, where fire is being used extensively as a land management practice (Itto 1997). It has negative environmental effects in the medium and long term due to the emission of many atmospheric pollutants and changes to the soil due to heat.

Fire destroys vegetation and consumes existing organic matter, also affecting animal species in or near the area. Furthermore, the uncovered soil is prone to erosion, as the layer of vegetation is removed from it, leaving it exposed to wind and rain. There is also a decrease in fertility, which affects the quality of new plants (Santín & Doerr 2016).

Regarding the damage caused by burning, it states that the main substances in the smoke generated by burning areas are polluting gases and particulate matter, which are present in excess in the atmosphere and are harmful to the environment and human health. Furthermore, according to CETESB (2021), the most generated product from burning is smoke, which represents 64% of the main sources of air pollutants in Brazil, without considering mobile sources.

Therefore, measuring and controlling air quality are important tools for understanding fire outbreaks and pollutants associated with burns. Several studies point to the correlation between atmospheric pollution and mortality and morbidity rates, as shown in a 2013 study. This work presents the main epidemiological studies carried out in Brazil on the association between air pollution and cardiovascular diseases (Saldiva & Coêlho 2019). The use of remote sensing in air quality studies is still underexplored, but it has great potential. Some

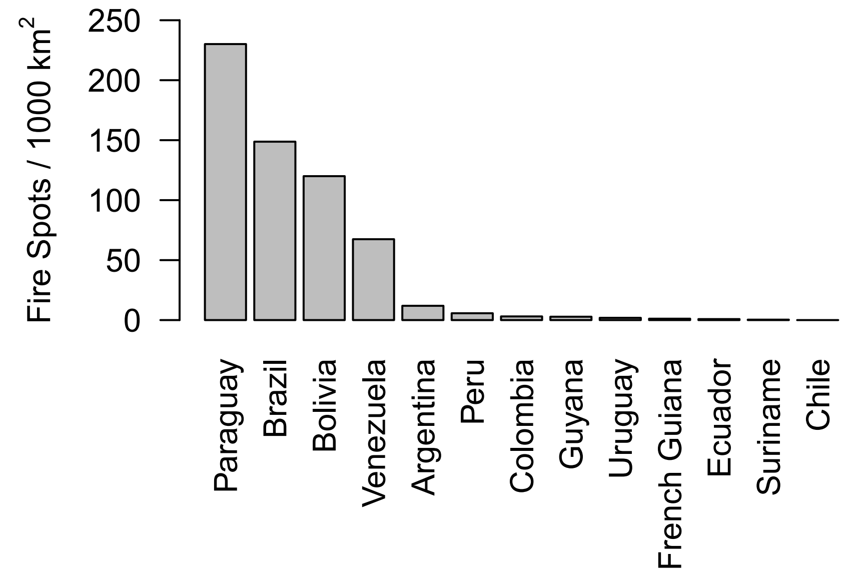

Figure 1. The ratio of hot spots by country area in South America between 2000 and 2006. Source: INPE 2008.

environmental satellites, such as TERRA, which uses the MOPITT sensor to measure CO; and AQUA, with an Atmospheric Infrared Sounder (AIRS) sensor for O_3; TERRA and AQUA which use the MODIS sensor for AOD measurements; and the OMI sensor, which is located on the satellite AURA and measures NO_2, have been shown to be alternative and complementary tools for monitoring pollutant concentrations (Gassó 2016). These tools have global coverage and provide information on atmospheric composition and surface attributes. The application of remote sensing techniques is fundamental because the databases generated by the various satellites in Earth's are important sources of information about the dynamics occurring on Earth's surface (Roza & Ribeiro 2013).

The use of sensing techniques to analyze burning and forest fires is increasing because they can present a summarized view, with broad coverage and repeated temporal sampling; in addition, they are able to provide data from large and difficult-to-access regions at low cost and at greater speed than field analyzes (Schepers et al. 2014).

Considering Brazil's specificities, detecting fires through remote sensing is the most viable method due to the territorial extension, the magnitude and diversity of forest ecosystems, and the significant number of fire occurrences recorded throughout the country (Batista 2014).

Currently, there are several satellites in orbit that carry different types of sensors with different resolutions, as well as techniques for detecting impacts caused by fires in tropical countries (Roza & Ribeiro 2013).

The objective of this study is to analyze the concentrations of atmospheric pollutants in the Pantanal region and their relationships with fire outbreaks, fire radiative power, and the amount of rain in the region from 2016 to 2021.

MATERIALS AND METHODS

Study Area

The studied area is in the border region between Mato Grosso and Mato Grosso do Sul, encompassing the entire Pantanal biome in the Brazilian territory, with latitudes ranging from -22.0 to -15.5 and longitudes ranging from -60.0 to -55.0.

Pantanal is in the center of South America and constitutes one of the largest extensions of continuous wetlands in the world; it is in the upper Paraguay River basin, which is approximately 496,000 km² in length (Carvalho 1986). In Brazil, the Pantanal is in the states of Mato Grosso and Mato Grosso do Sul, covering an area of 168,000 km² and the remaining area is in Bolivian and Paraguayan territories (Carvalho 1986).

The Pantanal Plain is an immense depressed area, along which the Paraguay River, which flows from north to south, collects water from the rivers that drain the surrounding plateaus, some up to 700 m high. Thus, what is called the Pantanal is a set of distinct, diverse, and complex landscapes, mainly related to the rivers of the sub-basins that form the Paraguay River (Guimarães et al. 2014). In each of these sub-basins, there are different water regimes, soil types, rocks, and geological structures that differ from each other, influencing the distribution of fauna and flora. However, even with the different water regimes between the sub-basins, the annual rain cycle (with seasons of flooding and drought) is the regulatory phenomenon of the biome physical environment of the biome for all sub-basins (Guimarães et al. 2014).

Due to the proximity of the biome to the equatorial line, the region has high levels of solar radiation, which is associated with the region's topography and is responsible for generating the biome's climate system (Guimarães et al. 2014). The Pantanal climate is classified as

Figure 2. Location of the Pantanal on the map of Brazil. Source: www.significados.com.br/pantanal.

humid tropical which gives the region a peculiar characteristic that can be divided into flood, dry, and low water periods. The climate is hot and humid in summer, with an average temperature of 25 °C (minimum 15 °C and maximum 34 °C), and the average relative humidity is 82% (Guimarães et al. 2014). In winter, due to air masses coming from the South Pole, among other variables, the temperature drops drastically, reaching less than 10 °C between April and September; however, air humidity remains high due to evapotranspiration resulting from the evaporation of water from the soil and evapotranspiration (Guimarães et al. 2014).

In addition to these seasons´ divisions, another Pantanal´s climate characteristic is the rainfall seasonality, which is not distributed homogeneously throughout the year. As stated by Guimarães et al. (2014), the rain in this biome is concentrated in some periods of the year. In summer, the volume of rainfall is much higher than in winter, characterizing summer as a rainy season, also known as the flood period. During this period, the rainfall is approximately 300 mm/month; in winter, the dry season, the rainfall is approximately 100 mm/month (Guimarães et al. 2014). Despite its generally humid climate with high rainfall, the Pantanal remains highly susceptible to wildfires. Frequent thermal inversions associated with regional and Bolivian circulation patterns trap pollutants near the ground, unlike other Brazilian biomes where synoptic and global-scale circulation facilitate faster dispersion. Additionally, the low altitude plain of the Pantanal concentrates pollutants, contrasting with other Brazilian regions' varied topography that allows for better dispersal.

Data

This study used NO_2 concentration data from the OMI sensor aboard the AURA satellite, CO, SO_2, OC, and BC taken from a reanalysis of the NASA MERRA-2 model.

The global NO_2 product of level 3 and the 0.25 x 0.25 degrees grid (OMNO2d) was used. The OMNO2d data product level 3 are good quality grouped pixel-level data and "are calculated on average" into global grids of 0.25x0.25 degrees. This product contains the total column and the total tropospheric column of NO_2, for all atmospheric conditions and for sky conditions in which the cloud fraction is less than 30%. In this research, tropospheric column data with less than 30% cloud fraction was used. OMI is a nadir viewing spectrometer covering the 264-504 nm spectral region that has performed atmospheric chemistry measurements in the 420-630 nm band since 2004 aboard NASA's Earth Observing System (EOS) - Aura satellite. Aura follows a sun-synchronous, near-polar orbit (705 km altitude), with an ascending local equator crossing time of 13:45 h. OMI observations provide complete global coverage in one day with a nominal land footprint of 13 × 24 km2 at nadir. It measures several pollutants, such as NO_2, SO_2, BrO, HCHO, and aerosols (Levelt et al. 2006).

MERRA-2 atmospheric reanalysis produces long-term records of high global spatial and temporal resolutions of meteorological fields and the composition of the Earth's atmosphere using a data assimilation methodology (Kalnay 2002), in which satellite and ground-based observations are combined with the general circulation model (GCM) simulations in an optimal statistical manner. The Modern Era Retrospective Analysis for Research and Applications (MERRA) was the first reanalysis generated using the Goddard Earth Observing System (GEOS) data assimilation system (DAS) by the Global Modeling and Assimilation Office (GMAO) from NASA (Rienecker et al. 2011). MERRA, first released in 2009, covered the years 1979 to 2015 (production ended on February 29, 2016). It was followed by the MERRA version 2 (MERRA-2) dataset that was used in this work.

NO_2, CO, SO_2, OC, and BC concentrations in the atmosphere near the surface refer are reported as monthly averages in the studied region from January 2016 to December 2021, and the data used were downloaded from https://giovanni.gsfc.nasa.gov/giovanni/. The software used to produce the pollutant concentration figures was the NCL (NCAR command language) from NCAR.

Daily data on monthly accumulated rainfall, analysis of hot spots and fire radiative power were also obtained using average daily data from different satellites from 2016 to 2021 from BDQueimadas/INPE (https://queimadas.dgi.inpe.br/queimadas/bdqueimadas).

This study analyzed pollutant concentrations through satellite data for NO_2 and the MERRA-2 model for other pollutants, the sum of rainy days per month, fire outbreaks, and fire radiative power (FRP), to determine which season had the highest number of fires and to verify whether there was any relationship between the high number of fires and burnings and the amount of rainfall in the same season and region.

RESULTS AND DISCUSSION

Burning

Analyzing the forest fires that occurred in the Pantanal from 2016 to 2021 (Figure 3), revealed a significant increase in burning. The peak occurred in 2020 with 28,877 fire outbreaks detected in the region, which corresponds to 44.3% of the fire outbreaks recorded in the six years of this study. For 2020 and other years, the months with the highest number of outbreaks are August, September, and October (ASO). Highlighting that September is the month with the highest number of outbreaks detected, with an average of 3957.6 outbreaks, which corresponds to 36% of the average number of fire outbreaks for the entire year.

Analyzing the same data separately for the states of Mato Grosso (MT) and Mato Grosso do Sul (MS) (Figure 3), it becomes evident that this pattern shows no significant changes. In both states, the peak season for fire outbreaks occurs between August and October, with September having the highest number of outbreaks. On

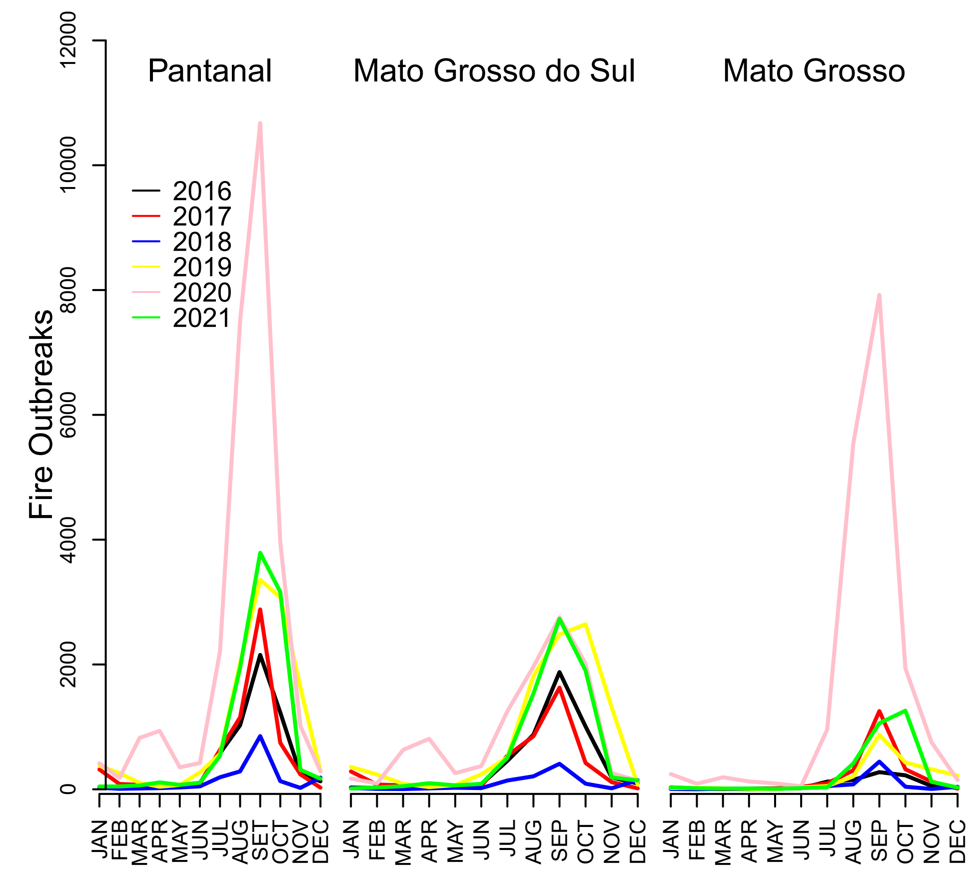

Figure 3. Average Monthly Fire Outbreaks (2016-2021). Source: The authors.

average, September records 1981 outbreaks in MS and 1971 in MT. Furthermore, 2020 presented the peak number of fire outbreaks for both states, with 10,722 in MS, which is 28% of all outbreaks detected in the last six years, and 18,055 in MT, which represents 66.5%. of all outbreaks from 2016 to 2021.

Wildfires in the Pantanal exhibit unique characteristics in pollutant emissions compared to other regions. High humidity, regional circulation patterns, and flat topography all play a significant role in how pollutants dispersed and concentrated within the biome.

The pattern of fire outbreaks remains consistent when examining the states individually, and the same pattern persists for fire radiative power (FRP), as depicted in Figure 4, which follows a similar pattern in both states when the highest FRP index occurs between August and October. The month with the highest index is September, with an average of 89.5 W m^{-2} considering the years of the analysis, while the periods with the lowest FRP levels are February, March, and April. The lowest FPR index is found in February, with a value of 26.3 W m^{-2}.

Despite 2020 having the highest number of fire outbreaks from 2016 to 2021, both MS and MT exhibited the highest FRP index in 2021, with values of 109.8 W m^{-2} for MS and 90.4 W m^{-2} for MT. Only in 2020 did MT exhibit an FRP greater than MS, as shown in Figure 5.

Comparing the amount of average rainfall in the two states, it is observed that June has the lowest average rainfall in both states, as demonstrated in Figures 6 and 7.

Comparing these values with the total precipitation per day, it becomes apparent that the period of the year with the highest number of

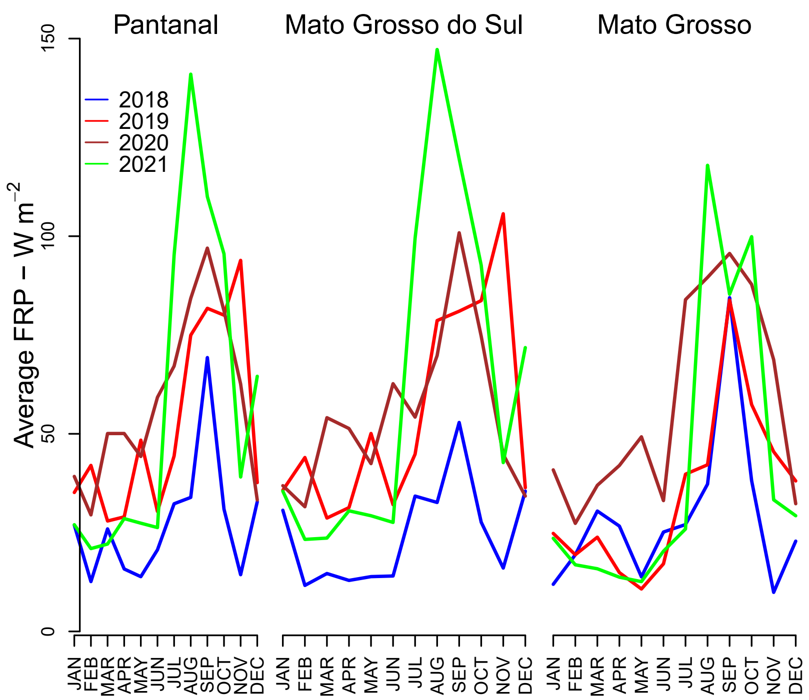

Figure 4. Average FPR by month for the Pantanal. **Source:** The authors.

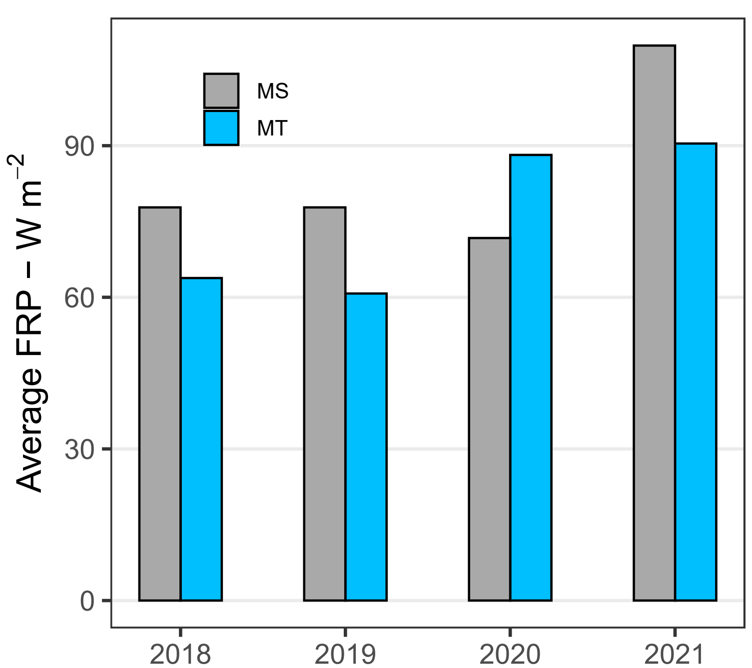

Figure 5. Annual average FRP in the MT and MS. **Source:** The authors.

fires is preceded by the quarter with the lowest average precipitation per day. This behavior is observed in all the analyzed years. Notably, 2020 received the least amount of rain, as shown in Figures 6 and 7.

Both states have the same rainfall pattern considering the total annual rainfall. Additionally, it is noteworthy that 2018 stands out as the year with the highest monthly average rainfall for both states. As depicted in Figure 7, MS experienced its lowest annual average rainfall in 2020, while

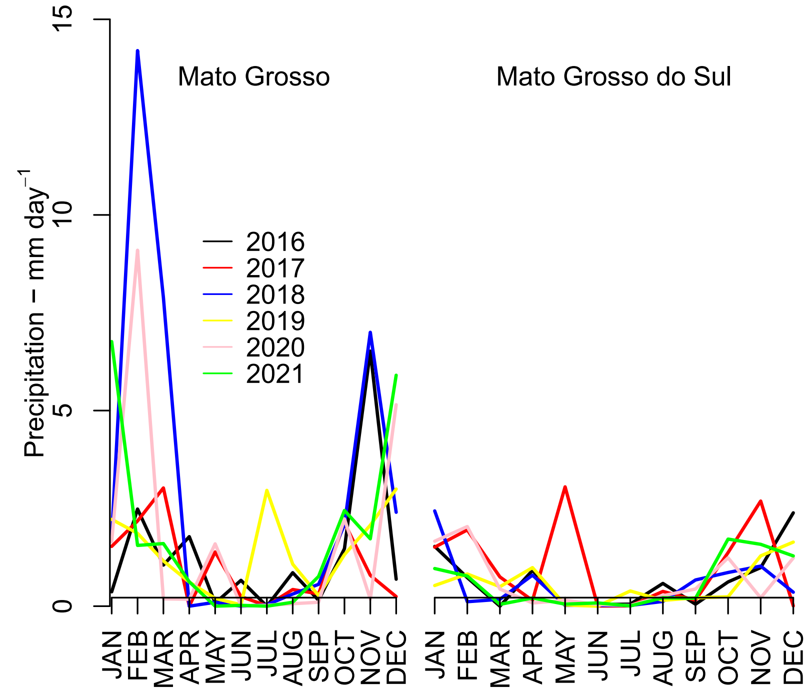

Figure 6. Monthly average rainfall in the MT and MS (2016-2021). **Source:** The authors.

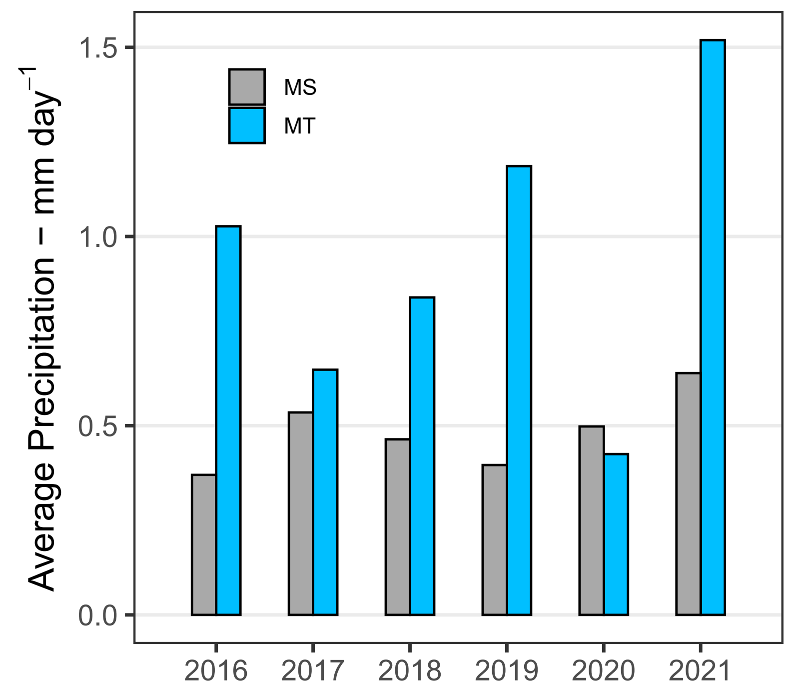

Figure 7. Annual average rainfall in the MT and MS (2016-2021). **Source:** The authors.

MT had its lowest annual average rainfall in 2019. Observing the two states in Figure 7, except for the years 2018 and 2021, which had 68% and 49% higher rainfall, respectively, compared to the average for the years 2016, 2017, 2019 and 2020, the rainfall values do not justify the increase of fire outbreaks number for the last three years of this analysis. These results emphasize that the rise in fire outbreaks is not related to droughts in the Pantanal region and it is probably related to the increase in burning caused by human action, as 2021 had a monthly average rainfall

48% higher than 2016, 2017, 2019 and 2020. In addition, it was the year with the highest FRP value and the second year with the highest number of fire outbreaks, followed by 2020, which had a record number of the fire outbreaks for the period studied.

Analysis of Pollutants in the Pantanal Biome

With the data obtained on pollutant concentrations in the Pantanal biome region, five sets of figures were developed showing the concentrations of pollutants for five different periods from 2016 to 2021: DJF – from December to February; MAM – from March to May; JJA – from June to August; SON – from September to November; and ASO – from August to October.

Figures 8 to 12 illustrate that the concentrations of all atmospheric pollutants analyzed in this study (CO, NO_2, SO_2, BC, and OC) increased in 2019, 2020, and 2021. The highest average was detected in 2020. The difference between the average concentrations from one year to another was more significant in the JJA, SON, and ASO periods, corresponding to the second semester of the year (winter and spring seasons). ASO (which encompasses the end of winter and the beginning of spring) was the period of the year where the greatest difference in concentration was observed, and the same

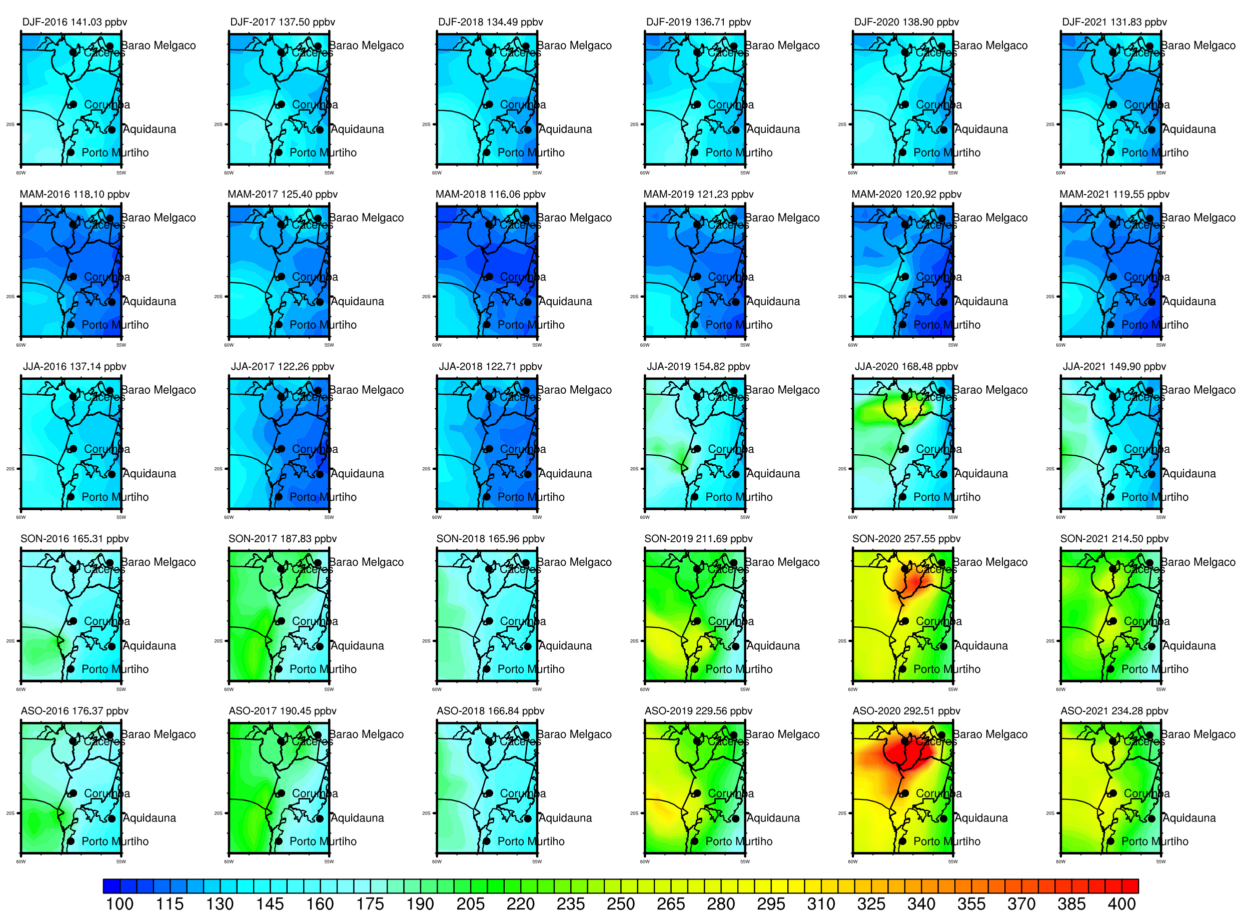

Figure 8. Seasonal concentration of CO (ppb) in the atmosphere near the surface of the Pantanal region from 2016 to 2021.
Source: The authors.

behavior was observed in the fire outbreaks and FPR analysis.

Figure 8 shows the CO (ppbv) concentration in the atmosphere near the surface of the Pantanal region obtained through MERRA-2 reanalysis data from 2016 to 2021. The atmospheric pollutant, CO, results from incomplete combustion of biomass burning and fossil and non-fossil fuels and can cause great damage to the environment. CO is an odorless and poisonous gas, that can inhibit the exchange of oxygen in the blood with the different tissues of the human body; if CO is inhaled in extreme concentrations, it can cause death from poisoning (Saldiva & Coêlho 2019). Figure 8 shows the lowest observed CO concentrations throughout the DJF and MAM periods. From JJA onward, the concentrations begin to increase, reaching higher values in the ASO period, the period with the greatest number of fires in the region. The highest recorded concentration of CO occurred on the Pantanal surface from June to November in 2019, 2020, and 2021. In comparison to the other years, 2020 presented the highest concentration of CO during the study period. The highest concentrations, in 2020, occurred in ASO and SON over the cities of Cáceres, Barão de Melgaço and Poconé (Pantanal Norte – MT).

Figure 9 shows the concentration distribution (molecules/cm²) of NO_2 in the atmosphere close to the surface in the Pantanal region obtained through data from the OMI sensor on the AURA satellite from 2016 to 2021. Nitrogen dioxide is a pollutant, frequently found in the atmosphere that originates from fossil fuel and biomass burning and can be extremely harmful to the environment and human health at high concentrations (Carvalho Junior & Lacava 2003).

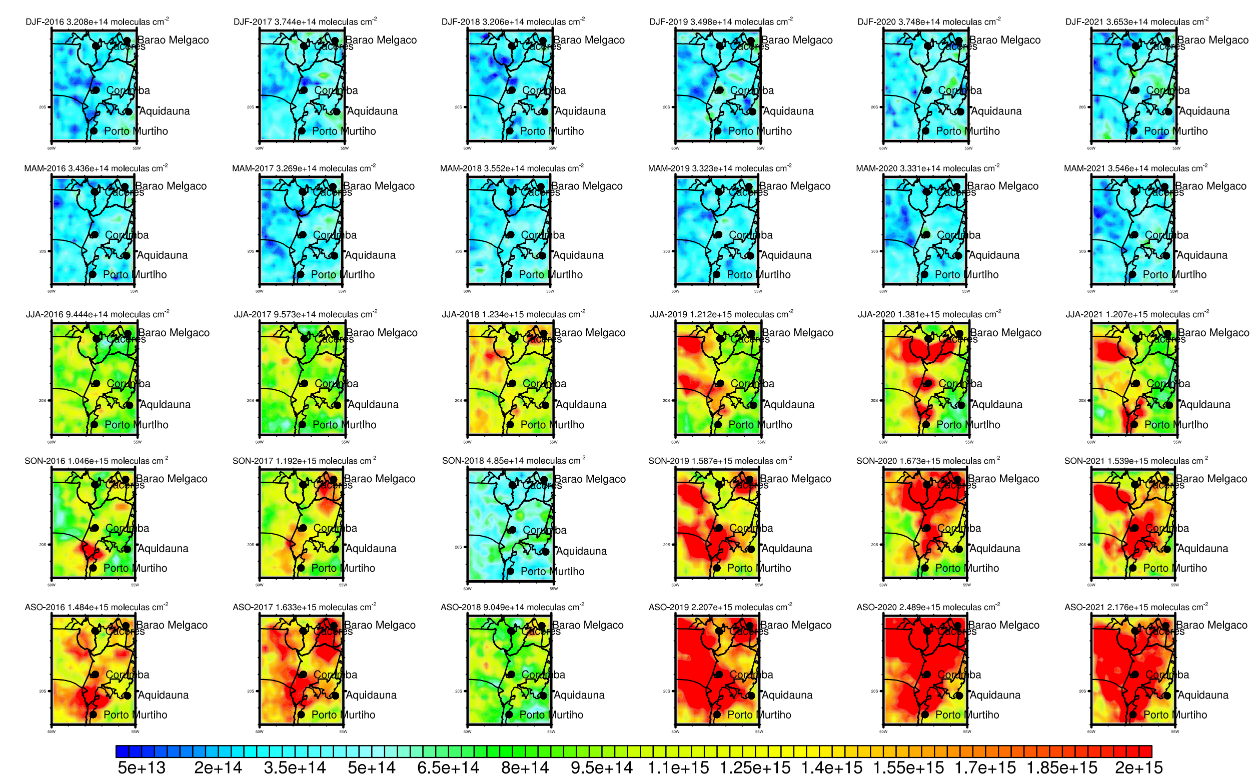

Figure 9. Seasonal concentration of NO_2 (molecules cm-2) in the atmosphere near the surface of the Pantanal region from 2016 to 2021.
Source: The authors.

NO_x is the general term that designates the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), the two nitrogen components most emitted in combustion processes (Carvalho Junior & Lacava 2003). Normally, the amount of NO formed is much greater than that of NO_2. However, once released into the atmosphere, NO quickly transforms into NO_2, and the mass emission rates of NO_x are always calculated considering its two compounds as exclusively NO_2 (Carvalho Junior & Lacava 2003).

NO_2 is a very common gas in the atmosphere, and high quantities of NO_2 cause damage to the environment, such as acid rain, the formation of photochemical smog, the increase in ozone in the atmosphere, and damage to human health, mainly related to breathing. (Nevers 2000). Therefore, NO_2 is considered an excellent environmental indicator for analyzing atmospheric pollution. For the analyzed time interval, seasonally, the lowest concentrations of NO_2 were observed during the period from DJF to MAM, for the first three years of this study (which presented the lowest concentrations). The highest concentrations were found in the period from June to November, highlighting that ASO was the period with the highest number of fires, mainly in 2020, during which the highest concentration was observed in the interval. An increase in this pollutant during the ASO in 2020, was observed over the southern region of Mato Grosso in the Pantanal, close to the cities

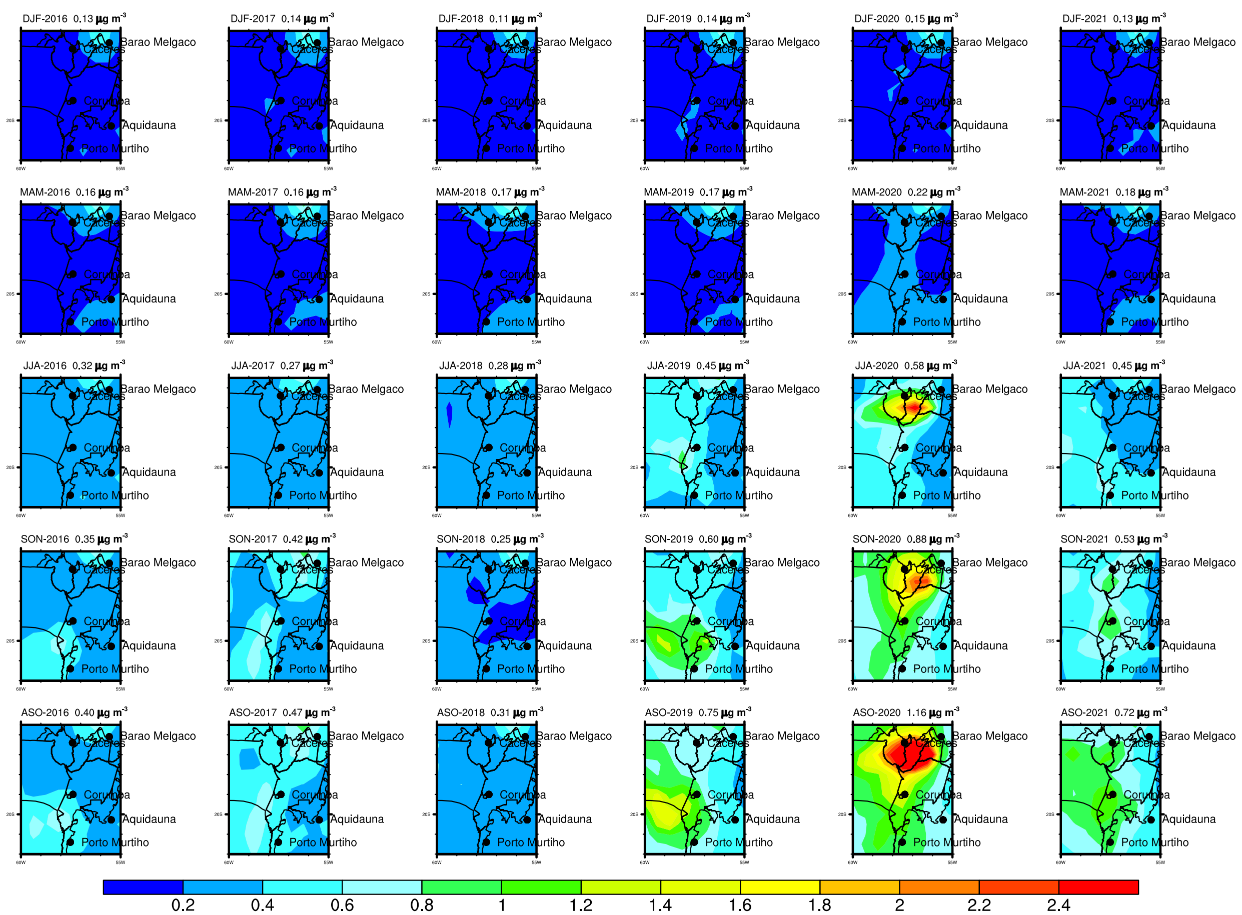

Figure 10. Seasonal concentration of SO_2 (microgram/m3) in the atmosphere near the surface of the Pantanal region from 2016 to 2021.
Source: The authors.

of Cáceres, Poconé and Barão do Melgaço, an anomalous behavior when comparing the ASO period to other years.

Figure 10 shows the concentration distribution of SO_2 (microgram/m^3) in the atmosphere over the Pantanal surface obtained through reanalysis data from the MERRA-2 model from 2016 to 2021.

Sulfur dioxide is a yellowish, soluble, and irritating gas that, according to Saldiva & Coêlho (2019), is an acidifying pollutant that can cause problems in the respiratory tract at high concentrations, especially in sensitive groups of people such as people with asthmatics. Furthermore, SO_2 is one of the main precursors of acid rain (Inomata et al. 2006). SO_2 is also the major generator of other pollutants in the atmosphere, such as ultrafine particles of sulfurous acid and sulfuric acid, which are harmful to the environment.

Gas enters the atmosphere through a series of anthropogenic activities and natural phenomena. Large quantities are released directly into the troposphere due to fossil fuel burning, and to a certain extent by the oxidation of organic matter in the soil, the oxidation of H_2S over the ocean, volcanic eruptions, and the burning of biomass (Eisinger & Burrows 1998).

Sulfur dioxide is very harmful to human health. Controlled studies indicate changes in

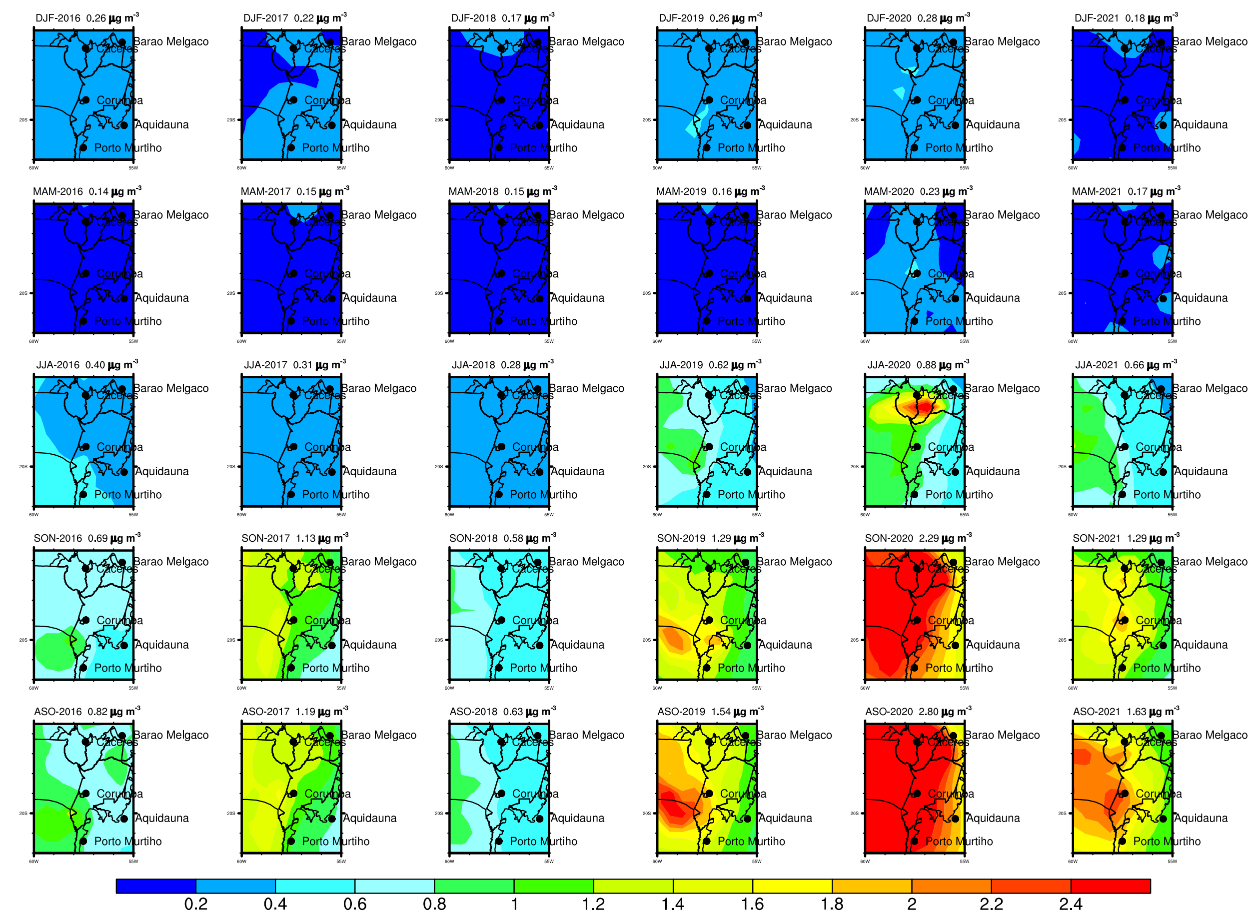

Figure 11. Seasonal concentration of black carbon (microgram per m³) in the atmosphere near the surface of the Pantanal region from 2016 to 2021.
Source: The authors.

lung function and respiratory symptoms after short periods of exposure to SO_2 (CETESB 2021). If dispersed in the atmosphere it can cause harm not only to humans and animals, but also to plants. Exposure to high levels of SO_2 can lead to plant leaf tissue necrosis (Carvalho Junior & Lacava 2003). The edges and areas between the leaf veins are particularly destroyed. Furthermore, part of the dispersed sulfur dioxide is converted into sulfuric acid; in this way, plants can be destroyed by sulfuric acid aerosols, in a much more devastating way than when drops of acid hit the leaves, as in the case of acid rain (Carvalho Junior & Lacava 2003).

SO_2 has similar behavior to the other two gases analyzed, CO and NO_2, indicating that these gases are emitted from the same source, mainly in the months with the highest concentrations (June to November). The same anomalous behavior was observed for SON and ASO in 2020, with greater concentrations in the northern Pantanal, in the cities of Cáceres, Poconé and Barão de Melgaço.

Figure 11 shows the black carbon concentration distribution (microgram/m³, obtained through MERRA-2 reanalysis data) in the atmosphere close to the surface of the studied region from 2016 to 2021. Black carbon (BC) is of great interest in dispersion and atmospheric source identification studies, because it is a characteristic of emissions derived from coal and diesel combustion, followed to a lesser

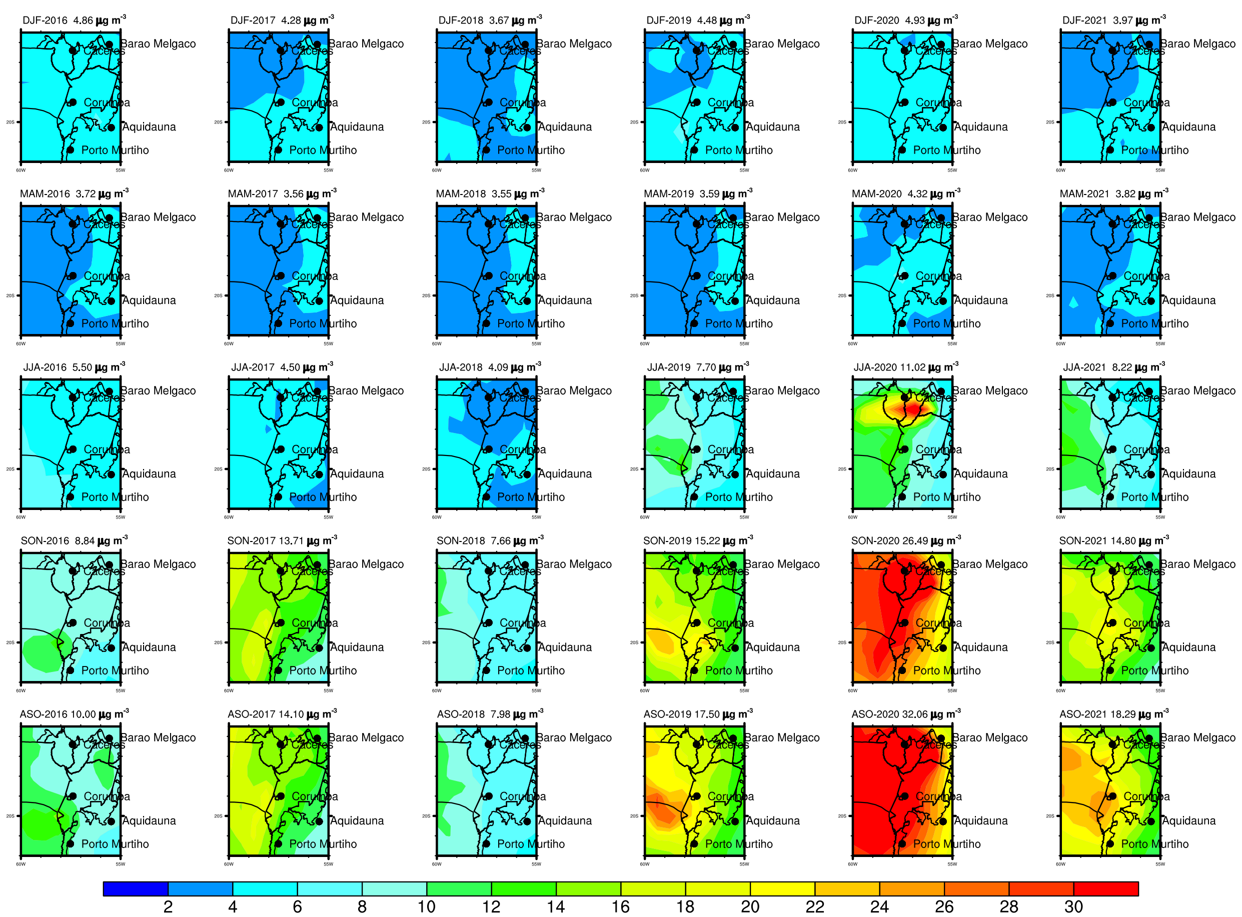

Figure 12. Seasonal concentration of organic carbon (microgram per m³) in the atmosphere near the surface of the Pantanal region from 2016 to 2021.

extent, by the burning of biomass (Santos et al. 2016). Pollutants are an important component associated with atmospheric particulate matter (PM), and their particles have a strong dark appearance, and vary in size, but are generally predominant in the PM2.5 and ultrafine fractions (less than 100 nm) (Ma & Birmili 2015).

According to Santos (2020), black carbon is considered a powerful absorber of solar radiation, and it can absorb a large spectral range of solar rays, which makes it a powerful contributor to the greenhouse effect on the planet. The main sources of BC include emissions from diesel vehicles, residential heating using coal or wood, and the open burning of biomass such as forests, lawns, and agricultural residues (Briggs & Long 2016).

An increase in the BC concentration is observed from June to November, as verified for the other pollutants of his study. However, unlike CO, NO_2 and SO_2, which presented higher concentrations in the southern region of Mato Grosso in ASO of 2020 (in the Pantanal close to the cities of Cáceres, Poconé and Barão do Melgaço), BC seems to have a greater influence on the dispersion of this pollutant with the direction and speed of the wind (which should be analyzed together with the direction and speed of the wind in a future study), propagating the concentration of BC from west to east over the entire Pantanal region, reaching greater intensity in the ASO period (with emphasis in 2020, which presented the highest concentration).

The high concentrations of this pollutant in the atmosphere indicate intense burning activity, as these regions do not have industries, and industrial emissions have no impact in this location. Black carbon can be used to trace anthropogenic activities responsible for its formation in remote regions. In combustion processes black carbon particles are initially formed in high concentrations as particles with diameters of 5-20 nm (Santos et al. 2016). However, they quickly coagulate to form fractal-type aggregates, that at first collapse into more compact structures on the order of 10 nm, due to the capillary forces of condensed vapors (Santos et al. 2016).

In this way, black carbon has proven to be an excellent pollution and public health indicator that is suitable for forest areas since a large part of black carbon comes from the burning of biomass (Santos et al. 2020).

According to the United States Environmental Protection Agency, the burning of solid fuels (coal and biomass) and diesel engines account for around 90 % of the emission sources of carbonaceous material (BC and OC), and the Vehicle traffic contributes 19 % of emissions. As a result, epidemiological studies have identified BC as a pollution indicator (Van Den Hove et al. 2020)

The organic carbon (OC) concentration distribution (microgram/m³) in the atmosphere near the surface of the studied region is presented in Figure 12. In the DJF and MAM periods, the lowest concentrations of this pollutant were detected. From JJA, it is already possible to notice a significant increase in this pollutant, starting from the west to the east of Pantanal, a similar behavior to that seen for BC. BC and OC are carbonaceous aerosols and, in this analysis, the distribution of CO, NO_2, and SO_2 gases have higher concentrations from June to November like BC and OC; however, the spread from west to east throughout the Pantanal is not as clear. The highest concentration peaks are observed in the ASO and SON periods in which concentrations up to approximately four times higher than the concentrations in the first half of the year are recorded. The highest concentration occurred in 2020 during the ASO period, in which high concentrations permeate the entire atmosphere close to the surface of the Pantanal region and travel from west to east, with the same characteristics as BC, making it evident that this OC does not come from biogenic sources, such as the vegetation of the Pantanal region, but rather from burning.

When analyzing the rainfall data for the same period, it becomes apparent that 2020 had practically the same average rainfall as the years 2016, 2017, and 2019. However, for the period of burning, mainly in the ASO of 2020, the concentrations of atmospheric pollutants such as CO, NO_2, SO_2, BC, and OC were respectively 29%, 31%, 50%, 52%, and 50% higher, respectively, than those in the first three years of this study (2016-2018). The year 2021, which has the second-highest average monthly rainfall in the period studied (including the dry period from June to November), has the second-highest concentration of atmospheric pollutants analyzed in this study from June to November, leading to the conclusion that the increase in fires during the dry season in the Pantanal region is not related to a decrease in precipitation and biogenic causes, but rather to burning caused by anthropogenic activities.

CONCLUSIONS

The NO_2, CO, SO_2, BC, and OC pollutant concentrations in the atmosphere near the surface of the Pantanal region from 2016 to 2021 were analyzed in the present study. The seasonality of high pollutant concentrations was identified in the SON and ASO periods when pollutants presented the highest concentrations for all the studied years. The highest pollutant concentrations were detected in 2020, which was the year with the highest number of fire outbreaks for the studied period, with 28.8 thousand outbreaks registered. For the period from 2016 to 2021, analyses were carried out to identify the concentrations of pollutants in the Pantanal region, and their possible relationships with the dry and rainy periods, as well as with the seasonal concentration of hot spots in the studied area.

The highest SO_2, CO, BC, and OC pollutant concentration were observed from July to October during the dry season when the rainfall volume was low and there was no dynamic action of rain "cleaning" the atmosphere and reducing the concentration of these pollutants.

In 2020, during the period from June to November, mainly in ASO, there was an atypical increase in the polluting gases CO, NO_2 and SO_2 over the southern region of Mato Grosso in the Pantanal, close to the cities of Cáceres, Poconé and Barão de Melgaço, which did not occur in the other years of this study. A spatial study, such as the approach used for these pollutants, incorporating variables such as fire radiative power (FRP) and aerosol optical depth (AOD) derived from satellite data, is recommended. For instance, data from the MODIS sensor on the Aqua and Terra satellites can be utilized. Additionally, the inclusion of meteorological variables such as wind speed and direction in the pollutant maps, as conducted in this work, is proposed for future research.

During JJA, similar behaviors are observed for both BC and OC, where BC and OC are carbonaceous aerosols, and in this analysis, the distributions of CO, NO_2, and SO_2 gases are relatively high during the period from June to November, similar to those of BC and OC, even though the spreading from west to east throughout the Pantanal is not as evident as that of BC and OC. The concentrations of CO, NO_2, and SO_2 are greater throughout the region and not spread like those of BC and OC, making it evident that this OC does not come from biogenic sources, such as vegetation in the Pantanal region, but rather from burning.

In the last three years studied, from 2019 to 2021, there was an even greater increase in the concentrations of pollutants during the dry season, which did not occur in the region in the first three years. The study of the concentration of pollutants, number of fire outbreaks, and FRP must be extended to monitor whether there is an increase in deforestation, burning, and consequently an increase in atmospheric pollution.

The dry season leaves vegetation more susceptible to natural or unintentional fires, however, intentional practices for agricultural and extractive purposes, among others, are the main cause of outbreaks, and are also responsible for the significant increase in the concentration of pollutants in the atmosphere. Therefore, anthropogenic modifications are the main causative agents of the scenario observed in the present study. The impacts on the local and even global environment are alarming since these pollutants modify the composition of the atmosphere. Another extremely important impact is related to public health because it can cause mild symptoms such as eye or nose irritation but can lead to more serious illnesses in the respiratory and cardiovascular systems. The impacts of deforestation and fires in the Pantanal biome on biodiversity can last for years and may even be irreversible. Therefore, the importance of taking action to prevent and monitor fire outbreaks by the population and competent authorities is reiterated. It is also important that air quality monitoring stations are installed in the Pantanal region. Pantanal's unprecedented 2019 fires (worst since 2009), highlight the critical need for enhanced research and monitoring tools to protect this globally significant biome. To achieve this, further study will incorporate MODIS Fire Radiative Power (FRP) and Aerosol Optical Depth (AOD) data, enabling us to refine our understanding of fire size, intensity, and smoke plume transport across the region and surrounding areas.

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