ISSN 1678-7226
Oliveira, K.; Veloso, L.; Emiliano, P.; Souza, A.; Brito, C.; Carvalho, M. (5 - 22) Rev. Geogr. Acadêmica v.19, n.1 (2025)

ANÁLISE QUANTITATIVA DO AR NO ESTADO DO MARANHÃO A PARTIR DO USO DO MODELO *HYSPLIT*

QUANTITATIVE ANALYSIS OF AIR QUALITY IN THE STATE OF MARANHÃO USING THE HYSPLIT MODEL

ANÁLISIS CUANTITATIVO DEL AIRE EN EL ESTADO DE MARANHÃO UTILIZANDO EL MODELO HYSPLIT

Kamilla Andrade de Oliveira
Dra. Meteorologia Agrícola, Universidade Federal do Maranhão, kamilla.andrade@ufma.br

Luciana Viana Veloso
Engenheira Agrícola, Universidade Federal do Maranhão, lucianaviana977@gmail.com

Paulo César Emiliano
Dr. Estatística, Universidade Federal de Viçosa, paulo.emiliano@ufv.br

Andreza Maciel de Souza
Engenheira Agrícola, Universidade Federal do Maranhão, andreza.maciel@discente.ufma.br

Carlos Alberto Rios Brito
Dr. Engenharia Aeronáutica, Universidade Federal do Maranhão, carlos.brito@ufma.br

Marcus Willame Lopes Carvalho
Dr. Agronomia, Universidade Federal do Maranhão, marcus.willame@ufma.br

RESUMO: Os incêndios Florestais são responsáveis pela emissão de inúmeros poluentes que causam a deterioração da qualidade do ar e afetam a saúde humana. Nesse sentido, objetivou-se avaliar o impacto das queimadas na qualidade do ar no Estado do Maranhão, através da análise de Material Particulado (MP), no período de 2010 a 2019. Para tal finalidade, foram obtidos dados de focos de calor, obtidos pelo Instituo Nacional de Pesquisas Espaciais (INPE), que permitiu estimar o período de pico de incêndios para o estado do Maranhão, $MP_{2,5}$ e realizar simulações em ambiente de sistema de informações geográficas (SIG) para massas de ar utilizando o modelo *HYSPLIT*. O Estado do Maranhão registrou 240.235 ocorrências de focos de calor para o período em estudo, com os meses de agosto a outubro apresentando o maior número de ocorrências. As concentrações de $MP_{2,5}$ apresentaram um comportamento sazonal, com o segundo semestre do ano apresentando as maiores médias, as regiões mais atingidas pelas altas concentrações de MP foram as regiões central e leste do Estado. O modelo *HYSPLIT* mostrou que as massas de ar que partem da região de Mirador, se deslocam principalmente no sentido oeste, apresentando variação ao longo do seu percurso. Os resultados encontrados mostram que algumas partes do estado necessitam de uma atenção maior com políticas públicas para toda sociedade.
Palavras-chave: Material Particulado; Incêndios Florestais; Pluma de fumaça; Qualidade do ar.

ABSTRACT: Wildfires are responsible for the emission of numerous pollutants that deteriorate air quality and impact human health. This study aimed to evaluate the impact of wildfires on air quality in the state of Maranhão by analyzing particulate matter from 2010 to 2019. Data on hotspots were collected to estimate the peak wildfire periods in Maranhão, along with PM2.5 concentrations and air mass simulations using the HYSPLIT model. The state recorded 240,235 hotspot occurrences during the study period, with the highest number of incidents occurring from August to October. PM2.5 concentrations exhibited seasonal variability, with the second half of the year showing the highest averages. The central and eastern regions of the state were the most affected by elevated levels of particulate matter. The HYSPLIT model indicated that air masses originating from the Mirador region primarily move in a westerly direction, with variations along their trajectory. The results suggest that certain areas of the state require more focused attention than others.
Keywords: Particulate Matter; Wildfire; Dust transport pathways, Air Quality.

RESUMEN: Los incendios son responsables de la emisión de numerosos contaminantes que causan el deterioro de la calidad del aire y afectan la salud humana. En este sentido, el objetivo fue evaluar el impacto de los incendios en la calidad del aire en el estado de Maranhão, a través del análisis de Material Particulado (MP), en el período de 2010 a 2019. Para ello, se obtuvieron datos de focos de calor, lo que permitió estimar el período pico de incendios para el estado de Maranhão, $MP_{2,5}$ y simulaciones de masas de aire utilizando el modelo HYSPLIT. El estado de Maranhão registró 240.235 ocurrencias de incendios durante el período de estudio, siendo los meses de agosto a octubre los que mostraron el mayor número de ocurrencias. Las concentraciones de $MP_{2,5}$ mostraron un comportamiento estacional, con la segunda mitad del año presentando los promedios más altos. Las regiones más afectadas por las altas concentraciones de material particulado fueron las regiones central y oriental del estado. El modelo HYSPLIT mostró que las masas de aire que parten de la región de Mirador, se mueven principalmente en dirección oeste, presentando variación a lo largo de su trayectoria. Los resultados muestran que algunas partes del estado necesitan más atención que otras.
Palabras clave: Material Particulado; Incendios Florestales; Vías de transporte; Calidad del Aire.

1. INTRODUCTION

Wildfire is an ancient practice in Brazil, occurring more frequently during the dry season and primarily associated with activities such as clearing and preparing agricultural land (Abreu et al., 2022). Nascimento et al. (2023) and Oliveira et al. (2023) explain that periods of low rainfall combined with low humidity favor the spread of fire.

Among the Brazilian biomes affected by environmental degradation, the Cerrado is one of the most impacted by fires and wildfire. This phenomenon has intensified in recent decades, primarily because this region is situated within Brazil's main agricultural frontier, the MATOPIBA region, which encompasses the states of Maranhão, Tocantins, Piauí, and Bahia (SILVA et al., 2021; CUNHA et al., 2021).

In this context, the state of Maranhão has recorded many hotspots. In 2019, it ranked third among Brazilian states for the highest fire outbreaks, accounting for nearly 10% of all outbreaks recorded nationwide (INPE, 2022). Beyond altering the landscape, fires and wildfires pose significant risks to human health due to the large quantities of pollutants emitted during combustion, including nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). The latter is toxic and highly harmful to human health (ROBERTS; WOOSTER, 2021; EKE; CINGIROGLU;KAYNAK, 2024).

Sarra and Mülfarth (2021) examined the impacts of fires in Brazil's Central-West region on cities in São Paulo state and found increased concentrations of PM2.5, PM10, and toluene, which correlated with rising hospital admissions due to respiratory issues in those areas. Additionally, Moreira et al. (2014) observed that periods of high pollutant concentrations in Tangará da Serra, MT, coincided with peak fire incidence in the Amazon, indicating a relationship between the two variables.

According to Santiago et al. (2015), particulate matter (PM) emitted during fires has smaller dimensions and lower density, prolonging its presence in the air and contributing to the formation of smoke screens. Consequently, depending on the meteorological conditions at the wildfire site, smoke, and other pollutants can be transported from one location to another, affecting air quality in nearby areas as well as more distant regions.

As a result, many studies have employed the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, designed for atmospheric transport and dispersion simulations. HYSPLIT, like other dispersion models, aids in understanding the dispersion processes of particles emitted during wildfire episodes and their potential impacts on local, regional, and global scales (MELECIO-VÁZQUEZ et al., 2023).

Although many studies have demonstrated the impact of fires on air quality in various Brazilian states and municipalities, the topic remains underexplored in the state of Maranhão due to a lack of data and information. Without developed and implemented methodologies, it is necessary to rely on alternative sources to assess whether pollutant concentrations in the state comply with national environmental legislation, thereby assisting in decision-making. In this context, the present study aimed to evaluate the impact of fires on air quality in Maranhão by analyzing particulate matter (PM2.5) from 2010 to 2019.

2. MATERIAL AND METHODS

2.1 Study area

The study was conducted in the state of Maranhão, located in the Northeast region of Brazil, between the parallels 1°01’ and 10°21’ South and the meridians 41°48’ and 48°50’ West. It shares borders with the states of Pará, Piauí, and Tocantins (Figure 1). Maranhão covers an area of approximately 329,651.495 km² and comprises 217 municipalities, including its capital, São Luís, organized into five mesoregions. The estimated population is 7,153,262 inhabitants (IBGE, 2020).

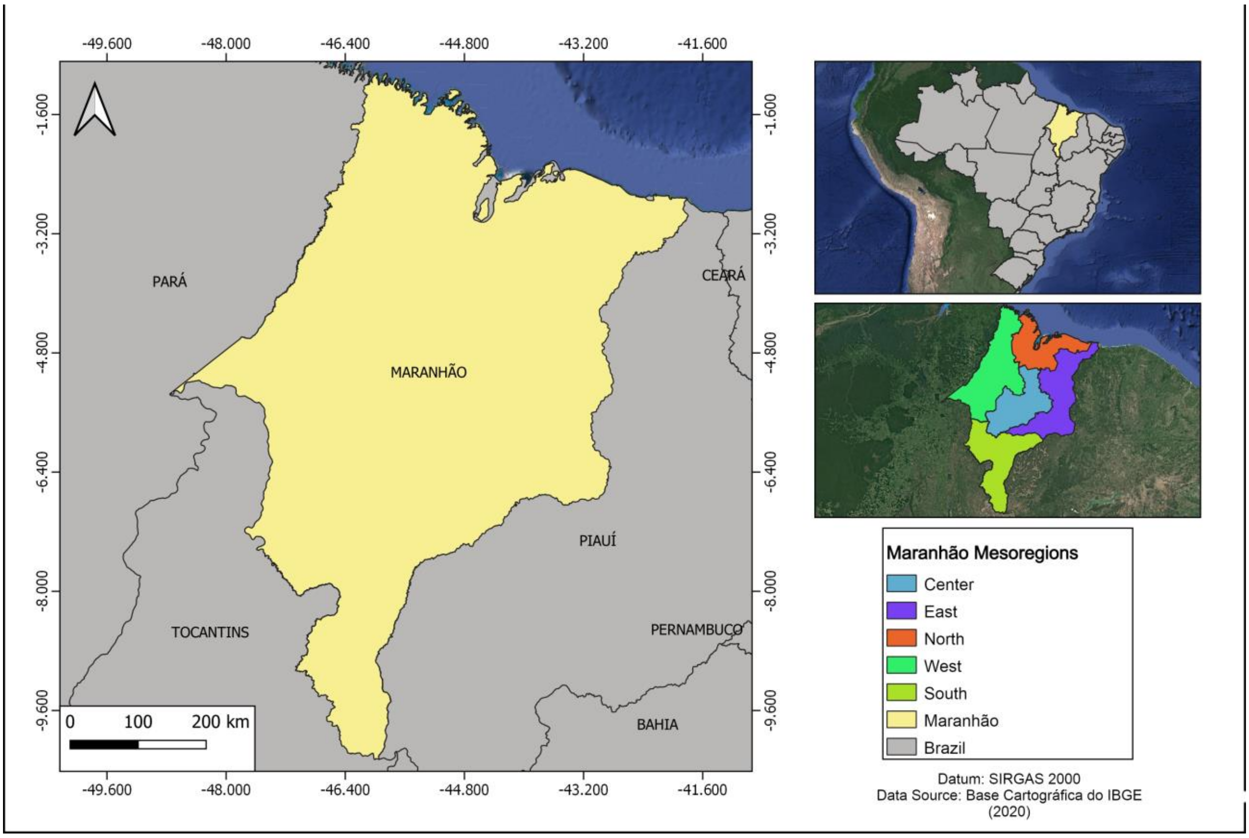


Figure 1 – Location map of the state of Maranhão, Brazil. Source: Prepared by the authors (2024).

According to Batistella et al. (2013, p. 100), the state of Maranhão is divided into three biomes: Amazon (34.8%), Caatinga (1.1%), and Cerrado (64.1%). The Amazon rainforest predominates in the northwest, the Cerrado in the south, and restinga vegetation and mangroves in the north (CHAVES et al., 2016). Based on the Köppen-Geiger climate classification, Maranhão has an Aw climate, characterized as tropical with summer rains (NASCIMENTO, BRAGA;ARAÚJO, 2017; CORRÊA; CARVALHO;MENDES, 2023).

The state experiences average annual temperatures ranging from 17.5 °C to 29.5 °C, with rainfall patterns varying by region. In the southern part, rainfall is concentrated from December to February; in the central area, from January to March; in the northern region, from February to April; and in the coastal plain, from March to May (BATISTELLA, 2013).

2.1. Database Acquisition and Processing

The hotspot data were obtained by downloading vector files in Shapefile format from the National Institute for Space Research (INPE) website. This data was utilized to identify the peak months of fires in Maranhão. The historical dataset for this study spans from January 2010 to December 2019, using data detected by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the AQUA M-T satellite.

Following data acquisition, ArcMap software (version PRO) was employed for data analysis, adhering to the methodological procedures proposed by Albuquerque (2017): 1) Reprojection of data to the UTM/SIRGAS 2000 coordinate system; 2) Creation of a geographic database with point geometry in Shapefile format; 3) Tabulation of the data; 4) Annual and monthly quantification of records.

2.1.1 Integrated Environmental Services System (SISAM)

Considering the lack of an air quality monitoring network in the state of Maranhão, data on concentrations of particulate matter (PM2.5) were obtained by downloading CSV files from the Integrated Environmental Information System for Environmental Health (SISAM/INPE) website. This data served as the basis for demonstrating the impact of fires on air quality.

The Excel® program was utilized to analyze the data, calculate the state's monthly and annual arithmetic means, and consider all available records from January 1 to December 31 of each year. From 2010 to 2017, SISAM provided data with 6-hour intervals, while in 2018 and 2019, the interval was 12 hours, starting at 00:00 for all years under study. Annual averages for each municipality were also calculated to determine how many municipalities exceeded the annual average value of 20 μg/m³, which is the maximum permitted according to the National Environmental Council (CONAMA) Resolution No. 491 of November 19, 2018 (SISAM, 2022).

The Pearson correlation was calculated between the hotspot data and PM2.5 concentrations using Excel's "CORREL" function. The Pearson coefficient (r) ranges from -1 to +1 and indicates the degree of correlation between two variables. Values close to +1 signify a strong positive association, while values close to -1 indicate a strong negative association. A coefficient value of zero means there is no correlation. In this study, the following values were adopted to classify the Pearson correlation: very weak ($0 \leq r < 0.19$), weak ($0.20 \leq r < 0.39$), moderate ($0.40 \leq r < 0.69$), strong ($0.70 \leq r < 0.89$), and very strong ($0.90 \leq r < 1.00$) (ANDRIOTTI, 2003).

2.1.2 Trajectory of air masses, Dust transport pathways

The trajectories of air masses departing from the hotspot region were calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (DRAXLER;HESS, 1998; STEIN et al., 2015). Developed by the National Oceanic and Atmospheric Administration (NOAA) in partnership with the Australian Bureau of Meteorology, the model was run online through the READY web system.

The coordinates of the area for which the trajectory was to be calculated were required to carry out the modeling. In this case, the chosen coordinates correspond to the municipality of Mirador (6.01° S; 44.47° W). The selection of this municipality is justified by its location in a region with a high annual density of heat sources.

The atmospheric data used to execute the model were sourced from the Global Data Assimilation System (GDAS). Starting at 18:00 UTC, a forward trajectory lasting 24 hours was set. The height selected was 50 meters above ground level (AGL), as aerosols are more abundant below 1 km, according to Shaik et al. (2019).

The simulation dates for each year were defined based on the methodology proposed by Silva Junior et al. (2020), which demonstrated that forest fires in Maranhão peak during the dry season, particularly in August and September. This methodology was also adopted in the present research.

3. RESULTS AND DISCUSSION

3.1 Analysis of hotspots, Wildfires

The results identified a total of 240,235 occurrences of hotspots in the state of Maranhão between January 2010 and December 2019 (Table 1). 2010 recorded the highest rate of hotspots, followed by 2012, 2015, and 2017, which together accounted for 124,588 hotspots—equivalent to 51% of the total occurrences for the entire study period. Conversely, 2018 and 2013 had the lowest rates of occurrences, with 13,892 and 17,455 hotspots, respectively.

Table 1 – Hotspots detected between 2010 and 2019 in Maranhão.

Month/Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
January	457	195	461	316	291	458	395	178	281	712
February	104	14	84	72	17	78	268	44	15	74
March	129	43	54	45	40	41	70	32	93	57
April	143	46	114	83	66	103	103	90	50	63
May	300	98	370	132	140	184	186	157	203	139
June	1225	689	987	603	786	850	693	644	738	749
July	2601	1159	3693	1332	2027	1616	2182	1973	1457	1078
August	6826	2192	10519	2374	5338	5411	3849	3001	2833	3366
September	11813	5086	7376	4312	4357	5502	3109	9243	3177	3667
October	4095	3171	5911	3221	5574	6387	5617	4538	1832	3645
November	6082	4038	2644	2368	3710	4159	3826	2706	2309	3158
December	2502	2584	2086	2597	2329	3647	1491	2970	904	1813
Total	**36277**	**19315**	**34299**	**17455**	**24675**	**28436**	**21789**	**25576**	**13892**	**18521**

Source: Prepared by the authors (2024).

This scenario is quite alarming for the state of Maranhão, as the increase in fire rates negatively impacts ecosystems and contributes to the emission of greenhouse gases (GHGs) into the atmosphere in this region (SILVA JUNIOR et al., 2020; ARAGÃO et al., 2023). According to Mapbiomas Fogo (2023), between 1985 and 2023, Maranhão ranked third in the national ranking of burned areas, with approximately 20 million hectares affected.

Silva et al. (2021) results support this assertion, indicating that the MATOPIBA region is responsible for more than half of the annual burned area in the Cerrado biome, with the states of Maranhão and Tocantins contributing over 73% of the total burned area in MATOPIBA between 2001 and 2018. Another factor to consider for the increase in fires in MATOPIBA is the changes in land use and coverage. There are significant trends of expansion of agriculture, pasture, and mining in this region, which ends up directly influencing the use of fire as a technique to increase agricultural production through the expansion of the agricultural area over the native vegetation of the Cerrado (CUNHA et al., 2021; ABREU et al., 2022).

When considering the monthly variation, the number of hotspots recorded from the second half of the year significantly increased, with the highest concentration mainly in August, September, and October. In November and December, there is still a high number of occurrences, but there is a small reduction compared to the previous three months (Figure 2). Considering the three peak months of hotspots over ten years, September accumulated the highest number, with 57,642 records.

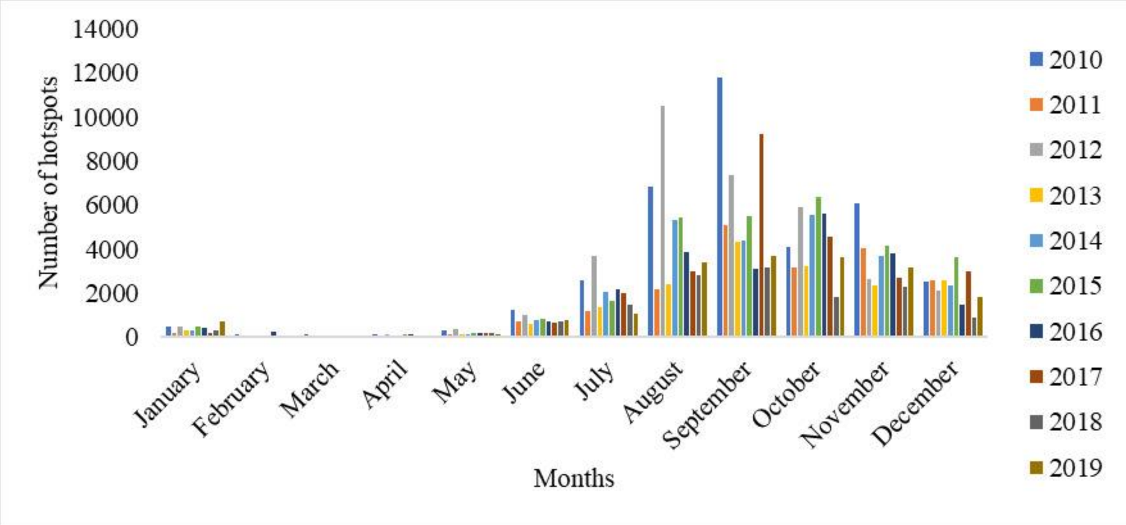


Figure 2 - Number of hotspots recorded monthly in Maranhão, 2010-2019. Source: INPE, Prepared by the authors (2024).

In Maranhão, the year's first half is characterized by high rainfall and milder temperatures, while the second half features a dry period with elevated temperatures. These conditions favor the occurrence and spread of fires during this time (SILVA JUNIOR et al., 2020; ABREU et al., 2022). Similarly, Abreu et al. (2022) indicate that the frequency of fires in the Cerrado biome is predominant during the dry season, with a slight increase starting in July and a significant surge, especially in August and September. Cordeiro et al. (2022) reported comparable results for the municipality of Marabá in the state of Pará and Ribeiro and Albuquerque (2020) for the state of Piauí. In both studies, the authors identified the second half of the year as the period with the highest incidence of hotspots, with the months of August to October showing the greatest records.

3.2. Particulate matter analysis

The PM2.5 was utilized as a metric to assess the level of air pollution in the state of Maranhão. Figure 3 displays the monthly averages for each year included in the study.

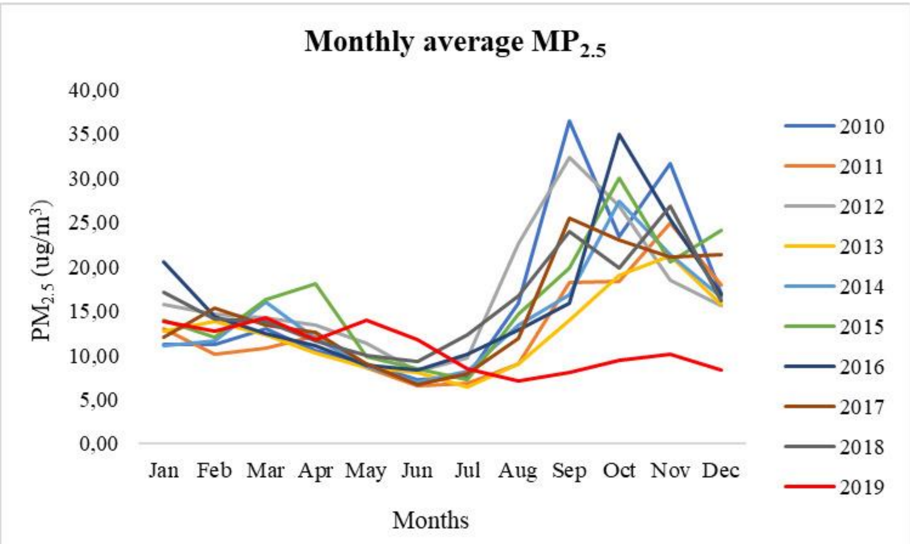


Figure 3 – Monthly variation of PM2.5 in the state of Maranhão. Source: Prepared by the authors (2024).

The analysis of the results indicates that the highest concentrations of particulate matter were observed in the second half of the year, increasing from August onward and remaining around 40 µg/m³ until November. A decrease in the monthly average is evident in December. This result aligns with the earlier observations regarding hotspots, suggesting that the high rate of fires influenced the rise in PM2.5 emissions during the year's second half.

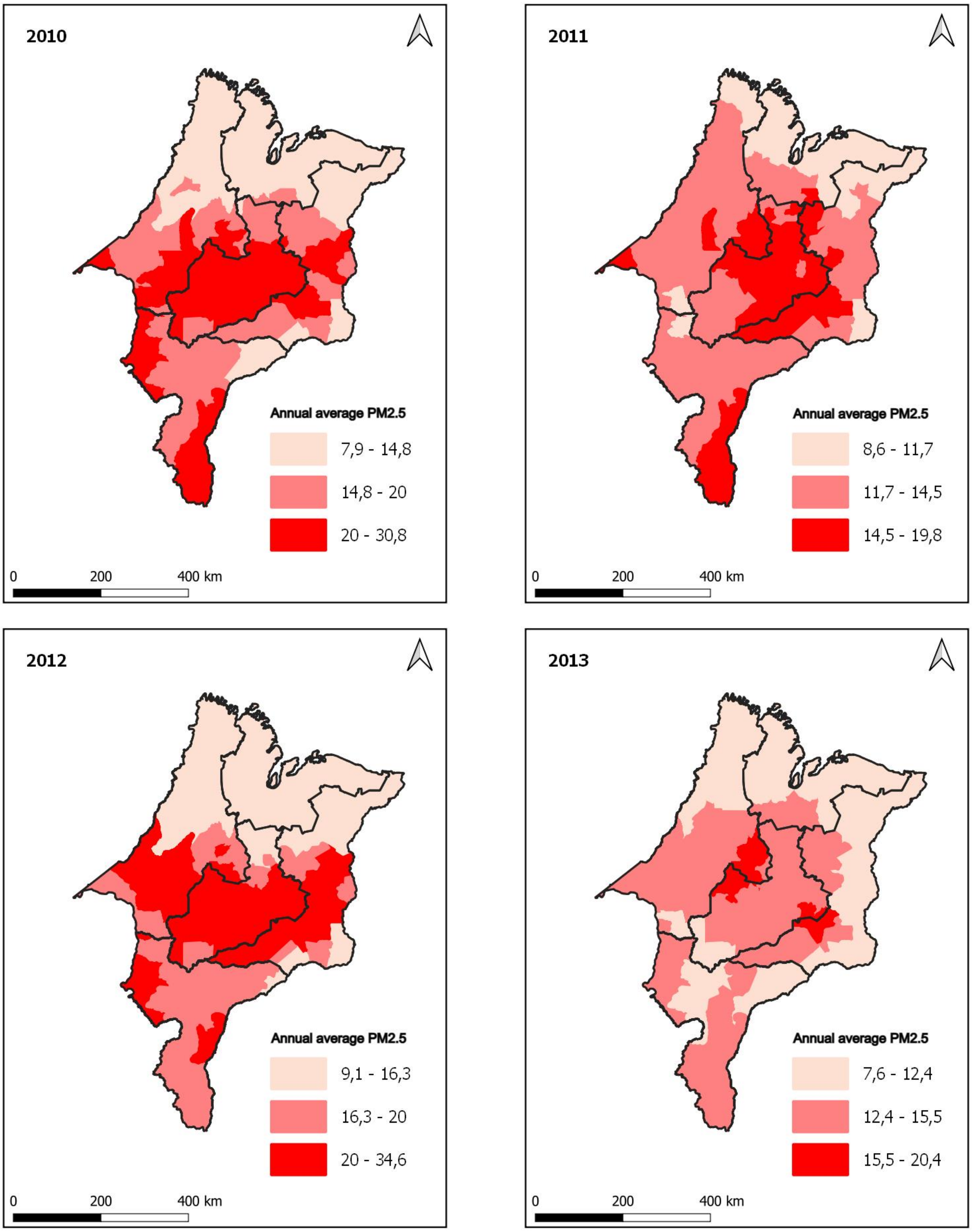
The decrease in monthly averages during the first half of the year was influenced by increased precipitation. Guerra and Miranda (2011) explain that rainfall facilitates the removal of pollutants from the atmosphere; therefore, more significant precipitation volumes correspond to lower concentrations of pollutants. Additionally, moist soil helps prevent the resuspension of particles into the air (FREITAS;SOLCI, 2009). Mataveli et al. (2018), in their estimation of monthly and annual PM2.5 concentrations in the Cerrado, also found that the highest averages of this pollutant occur between August and October. This pattern is primarily linked to the local dry period, which favors wildfire.

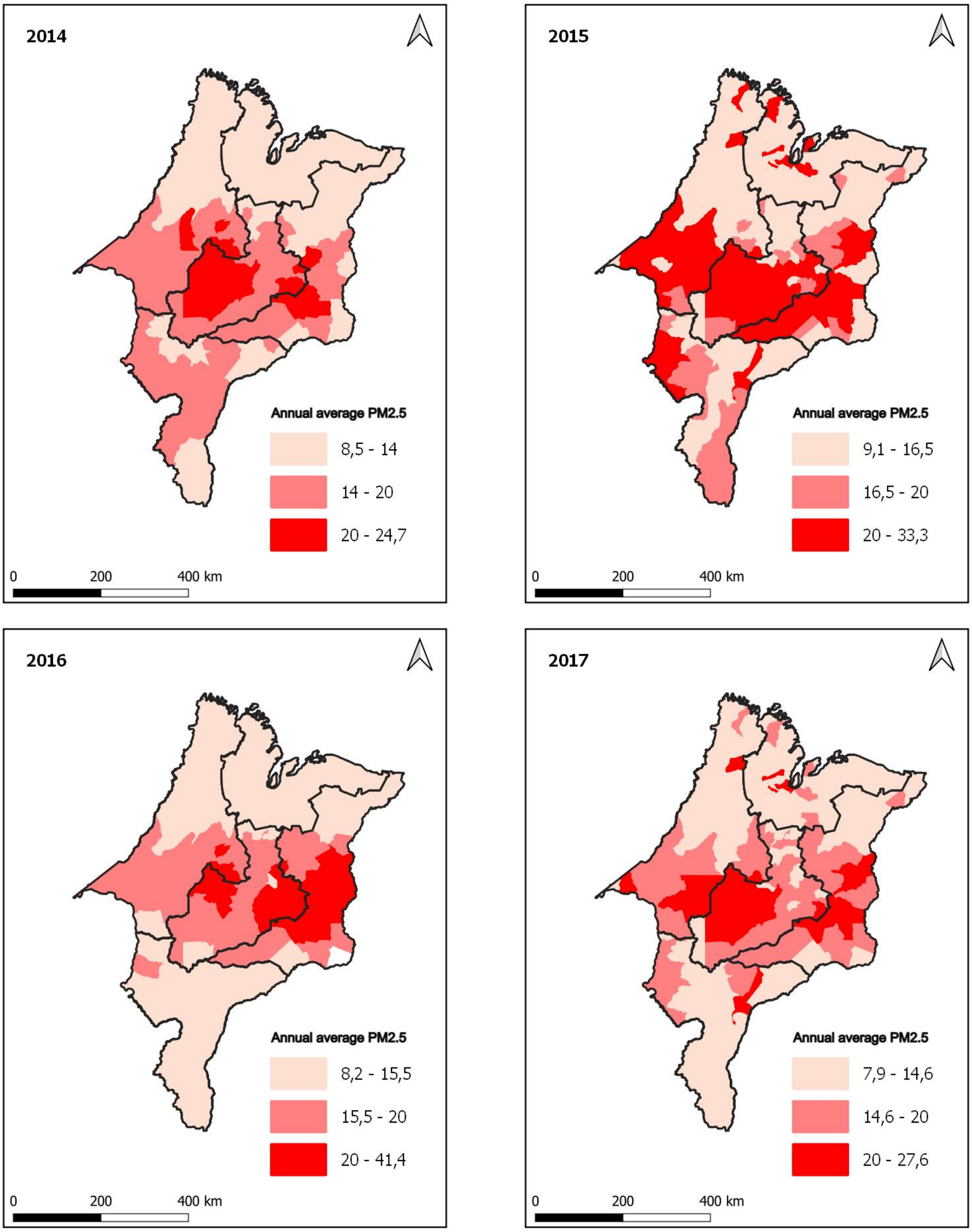
Table 2 – Annual monthly averages of PM2.5 for the state of Maranhão, 2010 to 2019..

Month/Year	**2010**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
January	11,17	15,75	12,76	11,04	14	20,61	12	17,09	13,79
February	11,28	14,64	13,84	11,60	12,02	14,42	15,38	14,13	12,69
March	12,94	14,23	12,33	16,00	16,33	12,48	13,39	13,77	14,24
April	10,59	13,41	10,20	11,85	18,09	11,08	12,55	11,69	11,74
May	9,06	11,34	8,63	8,74	9,90	8,89	8,98	9,96	14,00
June	7,29	8,21	8,12	7,03	8,48	8,31	6,75	9,33	11,80
July	7,62	9,72	6,48	8,18	7,23	10,16	7,90	12,32	8,48
August	15,84	22,65	8,98	13,41	14,66	12,91	11,91	16,78	7,06
September	36,46	32,35	14,02	16,83	19,86	15,91	25,55	23,93	8,11
October	23,42	26,88	18,99	27,39	30,00	35,01	23,06	19,88	9,47
November	31,62	18,49	21,29	21,36	20,58	25,39	21,16	26,83	10,18
December	17,00	15,63	15,70	16,58	24,15	16,86	21,31	16,12	8,29
Total	**16,19**	**16,94**	**12,61**	**14,19**	**16,31**	**16,06**	**14,97**	**15,99**	**10,81**

Source: Prepared by the authors (2024).

Sousa et al. (2020), in their study of the impacts of fires and deforestation in the Legal Amazon on air quality and human health, concluded that the low correlation between fire outbreaks and PM2.5 in 2019 is linked to the "Day of Fire." This event, which occurred on August 10, 2019, in the state of Pará, resulted in a significant increase in the number of hotspots and led to inspection actions and a 60-day ban on the use of fire throughout Brazil, as mandated by Decree 9.992/19 (Brasil, 2019). These measures likely contributed to a notable decrease in large-scale fires and reduced PM2.5 emissions from vegetation wildfire. According to CONAMA Resolution No. 491/2018, annual concentrations of PM2.5 must not exceed 20 µg/m³ (Brazil, 2018). Figure 4 illustrates the spatial distribution of annual averages of PM2.5 across municipalities in Maranhão.


2010
Annual average PM2.5
7,9 - 14,8
14,8 - 20
20 - 30,8
0
200
400 km
2011
Annual average PM2.5
8,6 - 11,7
11,7 - 14,5
14,5 - 19,8
0
200
400 km
2012
Annual average PM2.5
9,1 - 16,3
16,3 - 20
20 - 34,6
0
200
400 km
2013
Annual average PM2.5
7,6 - 12,4
12,4 - 15,5
15,5 - 20,4
0
200
400 km


2014
Annual average PM2.5
8,5 - 14
14 - 20
20 - 24,7
0
200
400 km
2015
Annual average PM2.5
9,1 - 16,5
16,5 - 20
20 - 33,3
0
200
400 km
2016
Annual average PM2.5
8,2 - 15,5
15,5 - 20
20 - 41,4
0
200
400 km
2017
Annual average PM2.5
7,9 - 14,6
14,6 - 20
20 - 27,6
0
200
400 km

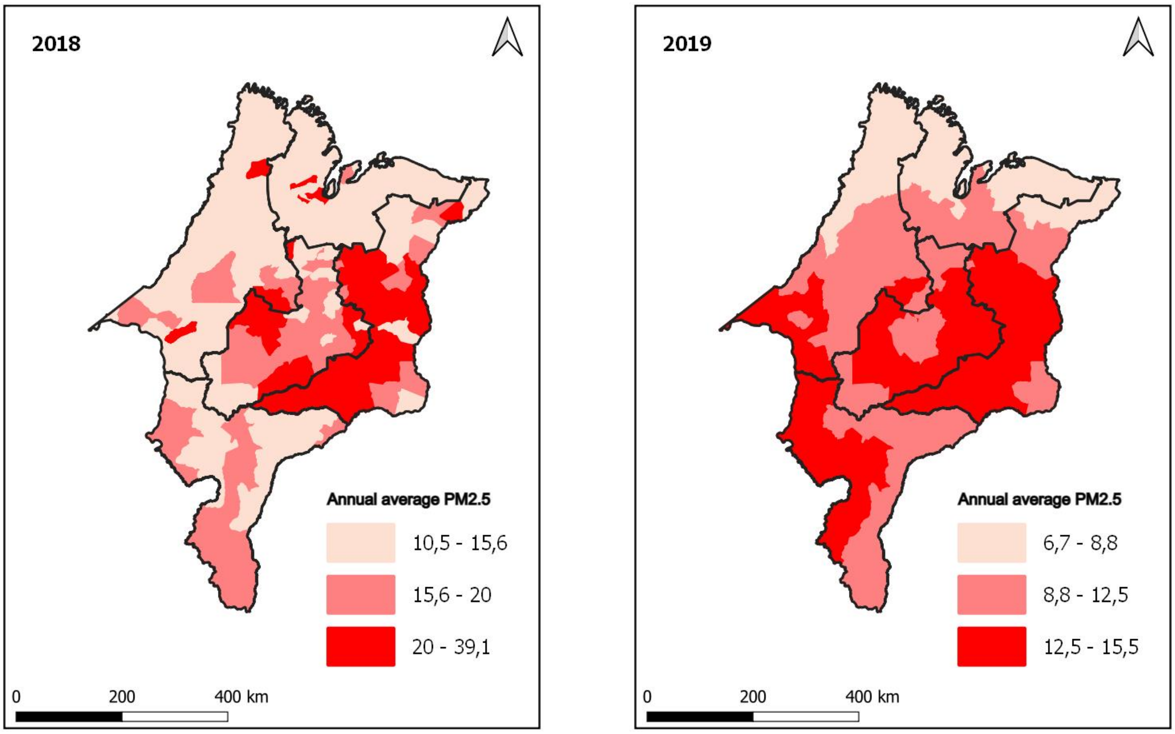


Figure 4 – Spatial distribution of annual averages of PM2.5 in municipalities in Maranhão. Source: Prepared by the authors (2024).

Between 2010 and 2011, a significant difference was noted in the number of municipalities that reported PM2.5 concentrations exceeding the limits established by Brazilian legislation, precisely 20 µg/m³. In total, 52 towns were identified with values above the average permitted by the CONAMA resolution in 2010, predominantly concentrated in the central part of the state. In contrast, no municipality exceeded the 20 µg/m³ limit in 2011, with annual averages ranging from 8.6 µg/m³ to 19.8 µg/m³. This variation can be attributed to the reduction in fire outbreaks from one year to the next, as 2010 recorded nearly twice the number of outbreaks compared to 2011.

In 2012 and 2013, they exhibited patterns similar to those of their predecessors, with an increase in locations impacted by high annual averages of PM2.5 in 2012 and a significant reduction in 2013 due to decreased fire activity. In 2012, 49 municipalities were identified with concentrations considered high, primarily concentrated in the central, eastern, and western regions of the state. Notably, in 2013, although two municipalities exceeded the annual average limit of PM2.5 of 20 µg/m³, the recorded values were slightly above this limit, ranging from 20.1 to 20.4 µg/m³.

Between 2014 and 2015, the number of municipalities with high PM2.5 concentrations rose to 69, with 19 in 2014 and 50 in 2015. During these two years, the state's central region once again accounted for a large proportion of municipalities with elevated particulate matter averages. However, in 2015, the eastern and western areas also experienced many municipalities affected by high concentrations. According to IBAMA (2015), Maranhão faced intense fire episodes in 2015, particularly in indigenous lands. Among the western and central regions, the Araribóia Indigenous Land was significantly impacted, enduring a fire that lasted approximately 45 days and resulted in a burned area of around 220,000 hectares. Yang et al. (2022) note that smoke from fires can be transported over large distances, affecting the air quality of small and large cities.

In 2016, the number of municipalities exceeding the annual PM2.5 limit increased again, totaling 31. São João do Soter, located in the eastern mesoregion of the state, was particularly notable, with an annual average of 41.4 μg/m³—more than double the legal limit. Data from INPE indicate that the municipality recorded only 72 hotspots throughout 2016; however, it is situated in a region with a high annual wildfire density. The wildfire activities in neighboring cities may have influenced the air quality in São João do Soter (INPE, 2022).

In 2017, the state had 23 municipalities with annual particulate matter concentrations above the average. These municipalities were primarily distributed across the state's eastern, central, and western regions, with average PM2.5 concentrations ranging from 7.9 to 27.6 μg/m³. In 2018, despite a reduction in fire outbreaks, 37 municipalities exceeded the annual PM2.5 limit, with most of these municipalities concentrated in the state's eastern region. In addition to the high incidence of fires in this area and the fixed sources of pollution within each city, another factor that may have contributed to the deterioration of air quality in the eastern municipalities is the dispersion of pollutants from fires carried by winds from the neighboring state of Piauí. Piauí, which borders Maranhão, annually records many fires (RIBEIRO; ALBUQUERQUE, 2020).

In 2019, no municipality in Maranhão exceeded the acceptable levels of air pollution for PM2.5, with annual averages ranging from 6.5 to 15.5 μg/m³. This marked the best result among the ten years studied.

Table 3 - Correlation between wildfires hotspots and particulate matter.

Year	Correlation
2010	0,850
2011	0,748
2012	0,729
2013	0,483
2014	0,668
2015	0,668
2016	0,704
2017	0,741
2018	0,713
2019	-0,780

Source: Prepared by the authors (2024).

Most of the years studied demonstrated a positive correlation between the monthly records of hotspots and the monthly average of PM2.5, ranging from moderate to strong. Specifically, the years 2013, 2014, and 2015 exhibited a moderate positive correlation ($0.40 \leq r < 0.69$), while the other years—except for 2019—showed a strong positive correlation ($0.70 \leq r < 0.89$). This indicates that as the number of hotspots in the state increases, the values of particulate matter also tend to rise due to biomass wildfire.

In contrast, 2019 displayed a strong negative correlation, with a value of -0.78, indicating an inverse relationship between the two variables. This result was anticipated, as 2019 presented an atypical situation compared to other years, with the first half of the year recording higher PM2.5 averages than the second half.

3.3. HYSPLIT Trajectories

The Figures 5 and 6 illustrate the trajectories of air masses calculated using the HYSPLIT model. Although trajectories were calculated for multiple days, the ones presented in this work were selected based on the weeks with the highest hotspots during September of each year.

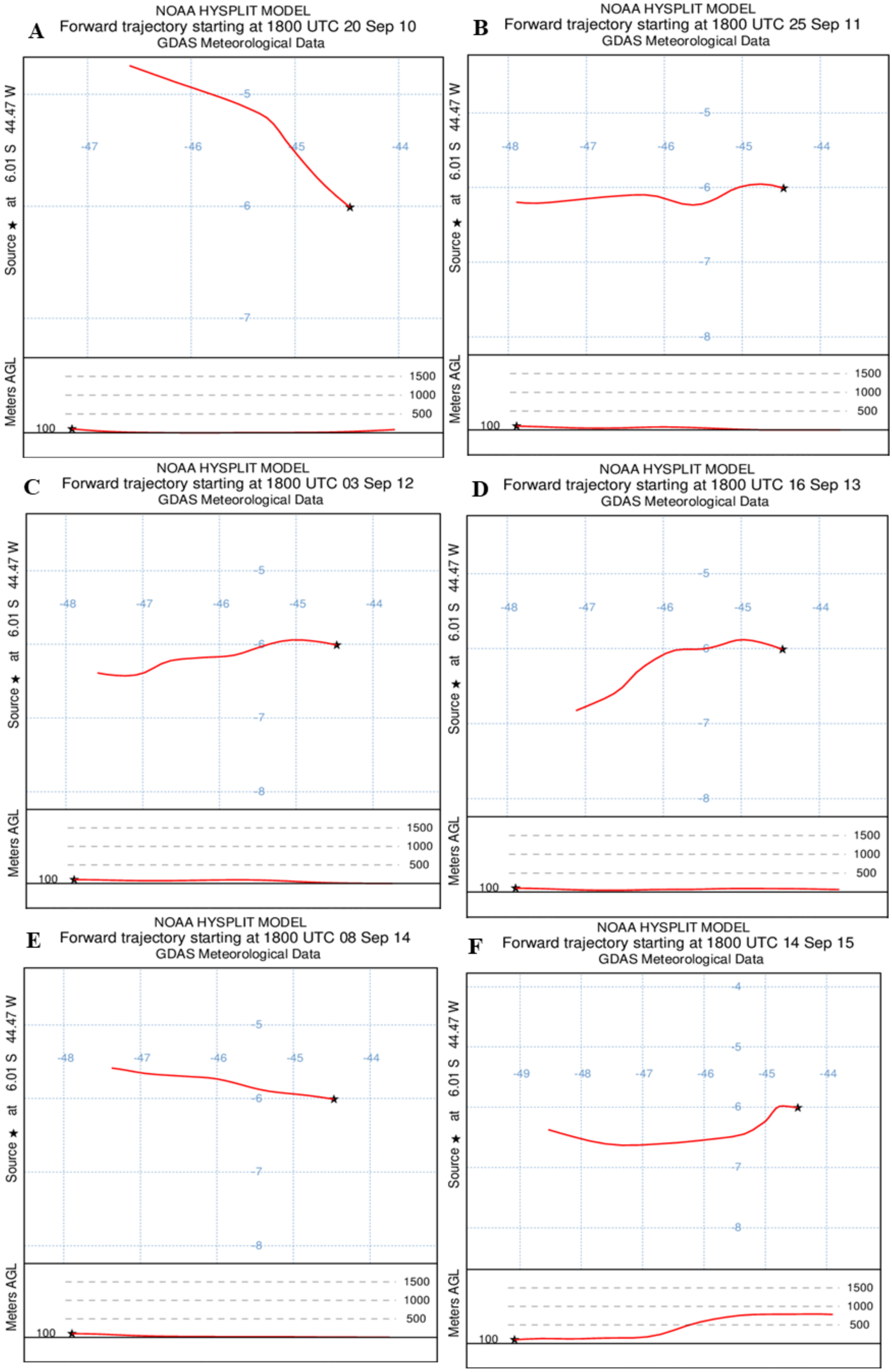

A
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 20 Sep 10
GDAS Meteorological Data
B
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 25 Sep 11
GDAS Meteorological Data
C
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 03 Sep 12
GDAS Meteorological Data
D
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 16 Sep 13
GDAS Meteorological Data
E
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 08 Sep 14
GDAS Meteorological Data
F
NOAA HYSPLIT MODEL
Forward trajectory starting at 1800 UTC 14 Sep 15
GDAS Meteorological Data
Source ★ at 6.01 S 44.47 W
Meters AGL
1500
1000
500
100

Figura 5 - Simulações *Hysplit* para os anos de 2010 a 2015. Fonte: Elaborado pelos autores (2024).

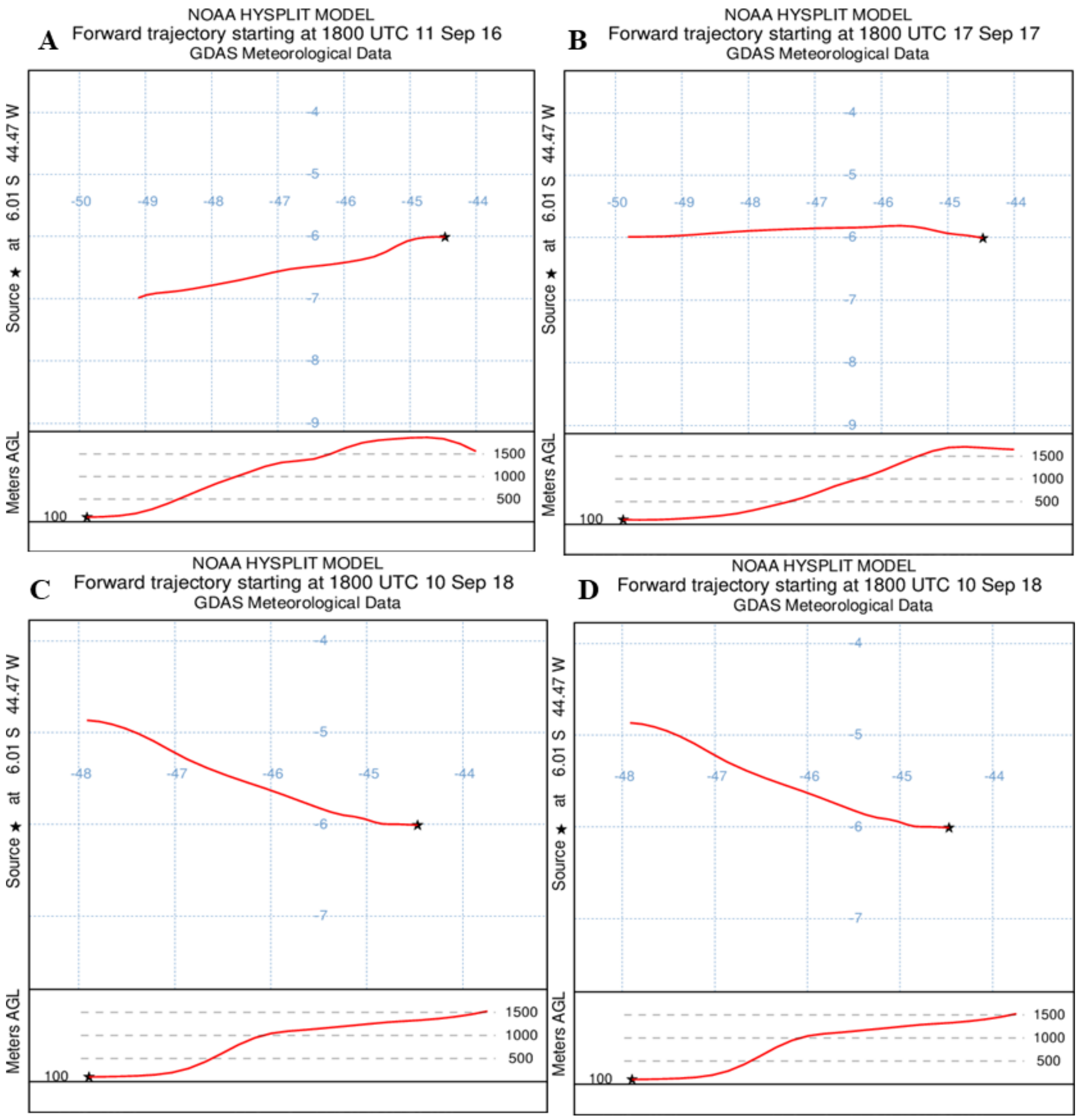


Figure 6 - Hysplit simulations for the years 2016 to 2019. Source: Prepared by the authors (2024).

The results indicate that the air masses departing from the Mirador region predominantly reach the state's central, western, and southern regions. Most aerosols are likely transported to downwind areas, with the central region being the most affected, as the air masses consistently pass through this area before reaching others.

The trajectories exhibit varying directions along their paths, allowing them to impact multiple cities. In Figures 5B, 5C, 5D, 6B, and 6C, the wind predominantly blows from the west, with minimal variation along the route. In contrast, Figures 5A and 6D show winds originating from the northwest, with trajectories remaining close to the ground. Figures 5E and 5F, along with 6A, initially direct westward; however, the paths shift to the northwest in Figure 5E and to the southwest in Figures 5F and 6A.

The municipalities in the central region of Maranhão warrant special attention regarding air pollution levels. In addition to the annual fires that impact this area, HYSPLIT simulations indicate that these municipalities may be influenced by pollutant concentrations from fires in the eastern part of the state, thereby increasing the likelihood of critical pollution days. Furthermore, the air quality of several municipalities in the western and southern regions is significantly affected by the transport of pollutants from the eastern and central areas. This is particularly concerning as air masses departing from Mirador and passing through the central state receive substantial contributions from fires occurring in the municipalities of Barra do Corda and Grajaú.

4. CONCLUSIONS

This research indicates that the state of Maranhão experienced a significant number of fires between 2010 and 2019, with 2010 marking the peak of fire outbreaks during the study period. The highest incidence of hotspots occurred in the second half of each year (July to December), particularly from August to October, coinciding with the dry season when precipitation is minimal.

Concentrations of PM2.5 exhibited a seasonal pattern closely tied to the fires prevalent during the dry season. The highest PM2.5 levels were observed from September to November, while the lowest concentrations were recorded between May and July, reflecting the influence of the rainy season that promotes pollutant dispersion.

High pollutant concentrations notably affected both the central and eastern regions of Maranhão, which were attributed to the numerous fires in these municipalities and the subsequent transport of pollutants across regions. Overall, Maranhão requires heightened attention regarding air quality standards, as elevated pollutant levels directly impact public health and well-being. Establishing an air quality monitoring network is essential for collecting in situ data and identifying priority areas for intervention.

REFERENCES

ABREU, M. C.; LYRA, G. B.; OLIVEIRA-JÚNIOR, J. F. de.; SOUZA, A.; POBOČÍKOVÁ, I.; FRAGA, M. S.; ABREU, R. C. R. Temporal and spatial patterns of fire activity in three biomes of Brazil. **Science of The Total Environment**, v. 844, p. 157138, 2022.

ALBUQUERQUE, E. L. S. Focos de calor na bacia hidrográfica do Rio Poti (Ceará/Piauí) a partir dos registros do satélite NOAA-18. **Os Desafios da Geografia Física na Fronteira do Conhecimento**, v. 1, p. 4708-4719, 2017.

ANDRIOTTI, J. L. S. **Fundamentos de estatística e geoestatística.** São Leopoldo: Editora Unisinos/ Universidade do Vale do rio dos Sinos, 166 p. 2003.

ARAGÃO, M. A.; FIEDLER, N. C.; RAMALHO, A. H. C.; MENEZES, R. A. S.; SILVA, E. C. G.; JUVANHOL, R. S.; BIAZATTI, L. D.; SILVA, E. F.; PEREIRA, R. S.; GUANAES, G. M. S.; LUCAS, F. M. F. Risk of forest fires occurrence on a transition island Amazon-Cerrado: Where to act? **Forest Ecology and Management**, v. 536, p. 120858, 2023.

BATISTELLA, M.; BOLFE, E. L.; VICENTE, L. E.; VICTORIA, D. C.; ARAUJO, L. S. de. **Relatório do diagnóstico do macrozoneamento ecológico-econômico do Estado do Maranhão**. Campinas, SP: Embrapa Monitoramento por Satélite; São Luís, MA: Embrapa Cocais, 2013. (Relatório técnico. Embrapa monitoramento por satélite, prod. 3, v. 1).

CHAVES, L. P. F. A.; SILVA, R. A.; AMARAL, Y. T.; COSTA, M. K. L.; SIQUEIRA, G. M. Biogeographical diversity of north mesoregion of the Maranhão state (Brazil). **Journal of Geospatial Modelling**, v. 1, n. 1, p. 19–31, 2016.

COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO (CETESB). **Poluentes**. Disponível em: <https://cetesb.sp.gov.br/ar/poluentes/>. Acesso em: 29 abr. 2022.

CORDEIRO, L. C.; SOUZA, M. B. de.; PAIVA, P. F. P. R..; GUSMÃO, M. T. A. de.; SILVA JUNIOR, O. M. da.; BRAGA, T. G. M.; BAIA, M. M. Análise temporal da ocorrência de focos de calor e uso e cobertura do solo no município de Marabá, Pará, Brasil. **Research, Society and Development**, v. 11, n. 1, p. e49011125198-e49011125198, 2022.

CORRÊA, W. C.; CARVALHO, M. W. L.; MENDES, T. J. Atualização da classificação climática e balanço hídrico climatológico no Estado do Maranhão. **Revista Brasileira de Climatologia**, v. 32, n. 19, p. 517-543, 2023.

CUNHA, E. R.; SANTOS, C. A. G.; SILVA, R. M.; BACANI, V. M.; POTT, A. Future scenarios based on a CA-Markov land use and land cover simulation model for a tropical humid basin in the Cerrado/Atlantic forest ecotone of Brazil. **Land Use Policy**, v. 101, p. 105141, 2021.

DRAXLER, R. R.; AND HESS G. D., 1997**: Description of the *HYSPLIT*_4 modeling system.** NOAA Tech. Memo. ERL ARL-224. NOAA Air Resoucers Laboratory, Sylver Spring, MD, 24 pp.

EKE, M.; CINGIROGLU, F.; KAYNAK, B. Investigation of 2021 wildfire impacts on air quality in southwestern Turkey. **Atmospheric Environment**, v. 325, p. 120445, 2024.

FREITAS, A. de. M; SOLCI, M. C. Caracterização do MP10 e MP2,5 e distribuição por tamanho de cloreto, nitrato e sulfato em atmosfera urbana e rural de Londrina. **Química nova**, v. 32, n. 7, p. 1750-1754, 2009.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE). **Geociências: Área Territorial Brasileira**. 2020. Disponível em: <https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial.html>. Acesso em: jan. 2022.

INSTITUTO BRASILEIRO DE MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS (IBAMA). **Brigadistas do Ibama Combatem Incêndio em Terra Indígena no Interior do Maranhão.** 2022. Disponível em: <http://www.ibama.gov.br/component/tags/tag/inpe>. Acesso em: jun. 2022.

INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE). 2022. **BDQueimadas** Disponível em: <https://queimadas.dgi.inpe.br/queimadas/bdqueimadas/>. Acesso em: 30/04/2022.

MATAVELI, G. A. V.; SILVA, M. E. S.; PEREIRA, G.; SANTOS, P. R.; CARDOZO, F. DA S.; LIMA, S. F. S.; FRANÇA, D. DE A. & SILVA, F. B. Modelagem da Contribuição do Cerrado sobre as Emissões Brasileiras de Material Particulado Fino (PM2,5 µm) Associadas à Queima de Biomassa. **Revista Do Departamento De Geografia**, p. 118-128, 2018.

MELECIO-VÁZQUEZ, D.; LAUTENBERGER, C.; HSIEH, H.; AMODEO, M.; PORTER, J. R.; WILSON, B.; POPE, M.; SHU, E.; WAESELYNCK, V.; KEARNS, E. J. A Coupled Wildfire-Emission and Dispersion Framework for Probabilistic $PM_{2.5}$ Estimation. **Fire**, v. 6, p. 220, 2023.

Ministério do Meio Ambiente (BRASIL). Decreto 9.992/19, de 28 de agosto, 2019. **Determina a suspensão da permissão do emprego do fogo.** 2019. Disponível em: <https://www.planalto.gov.br/ccivil_03/_Ato2019-2022/2019/Decreto/D9992.htm>. Acesso: 20 de setembro de 2024.

Ministério do Meio Ambiente (BRASIL). Resolução Conama n° 491, de 19 de novembro de 2018. **Dispõe sobre os padrões de qualidade do ar.** Diário Oficial da União. Brasília, DF: Imprensa Oficial. Disponível em:< https://www.gov.br/mma/pt-br/assuntos/noticias/conama-aprova-prazos-para-novos-padroes-de-qualidade-do-ar/copy_of_ApresentaonoConamaAdalbertoMaluf.pdf>. Acesso: 22 de setembro de 2024.

MOREIRA, P.S.P.; DALLACORT, R.; LIMA, I, F.; TIEPPO, R. C.; SANTOS, C. Concentração de material particulado na região de Tangará da Serra-MT, sul da Amazônia Legal. **Revista Brasileira de Geografia Física**, v. 7, n. 6, p. 1145-1152, 2014.

NASCIMENTO, A. L. da S.; TEIXEIRA, M. da S.; ALONSO, M. F.; NUNES, A. B.; LAUREANTI, N. C.; JAVARINI, L. P. Padrões sinóticos associados a ocorrência de incêndios florestais na Estação Ecológica do Taim e Campos Neutrais - Brasil. **Revista Brasileira De Climatologia**, v. 32, n. 19, p. 463–493, 2023.

NASCIMENTO, F. D. C. A; BRAGA, C. C; ARAÚJO, F. R. D. C. D. Análise estatística dos eventos secos e chuvosos de precipitação do Estado do Maranhão. **Revista Brasileira de Meteorologia**, v. 32, p. 375-386, 2017.

OLIVEIRA, J. G. de.; MASSI, K. G.; BORTOLOZO, L. A. P.; CUNHA, A. P. M. do A. The influence of climate parameters on fires in the Paraíba do Sul River valley, southeast Brazil. **Revista Ambiente & Água**, v. 18, p. e2923, 2023.

PROJETO MAPBIOMAS (MapBiomas Fogo) - Mapeamento das áreas queimadas no Brasil entre 1985 a 2023. 2023. Coleção 3. Disponível em: < https://brasil.mapbiomas.org/metodo-mapbiomas-fogo/>. Acesso: 20 de setembro de 2024.

RIBEIRO, K. V.; ALBUQUERQUE, E. L. S. Análise geoespacial da ocorrência de focos de calor no estado do Piauí (2010 a 2019). **Produção Técnica**. GEOAMBIENTE/UFPI: Teresina, 2020.

ROBERTS, G.; WOOSTER, M. J. Global impact of landscape fire emissions on surface level PM2.5 concentrations, air quality exposure and population mortality. **Atmospheric Environment**, v. 252, p. 118210, 2021.

SANTIAGO, A.; PRADO, R. J.; FILHO, P. M.; ALONSO, R. V. Caracterização do material particulado suspenso no ar de Cuiabá-MT no período de queimadas. **Revista Matéria**, Rio de Janeiro, v. 20, n. 1, p. 273–283, 2015.

SARRA, S. R.; MÜLFARTH, R. C. K. Impactos das queimadas da região Centro-Oeste do Brasil sobre as cidades do estado de São Paulo. **Brazilian Journal of Development**, v. 7, n. 5, p. 51237-51257, 2021.

SHAIK, D. S.; KANT, Y.; MITRA, D.; SINGH, A.; CHANDOLA, H. C.; SATEESH, M.; CHAUHAN, P. Impact of biomass burning on regional aerosol optical properties: A case study over northern India. **Journal of environmental management**, v. 244, p. 328-343, 2019.

SILVA JUNIOR, C. H. L.; CELENTANO, D.; ROUSSEAU, G. X.; MOURA, E. G.; VARGA, I. V. D.; MARTINEZ, C.; MARTINS, M. B. Amazon forest on the edge of collapse in the Maranhão State, Brazil. **Land Use Policy**, v. 97, p. 104806, 2020.

SILVA, P. S.; NOGUEIRA, J.; RODRIGUES, J. A.; SANTOS, F. L. M.; PEREIRA, J. M. C.; CAMARA, C. C.; DALDEGAN, G. A.; PEREIRA, A. A.; PERES, L. F.; SCHMIDT, I. B.; LIBONATI, R. Putting fire on the map of Brazilian savanna ecoregions. **Journal of Environmental Management,** v. 296, 2021.

Sistema de Informações Ambientais Integrado a Saúde (SISAM). **Ficha técnica Material Particulado d <2.5 µm ($PM_{2.5}$) Próximo da Superfície.** 2022. Disponível em: <https://queimadas.dgi.inpe.br/queimadas/sisam/v2/static/site/files/ficha_tecnica_concentracao_pm25.pdf>. Acesso em: 18 de maio de 2022.

STEIN, A. F.; DRAXLER, R. R.; ROLPH, G. D.; STUNDER, B. J. B.; COHEN, M. D.; NGAN, F. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. **American Metereological Society**, v. 96, n. 12, p. 2059-2077, 2015.

YANG, Z.; DEMOZ, B.; DELGADO, R.; SULLIVAN, J.; TANGBORN, A.; LEE, P. Influence of the transported Canadian wildfire smoke on the ozone and particle pollution over the Mid-Atlantic United States. **Atmospheric Environment**, v. 273, p. 118940, 2022.