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Extreme Wildfires in Brazil, in 2024, and their Impact on the Air Quality in Urban Areas

Queimadas Extremas no Brasil, em 2024, e seu Impacto na Qualidade do Ar de Áreas Urbanas

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In 2024, an exceptional drought with high temperatures and strong winds associated to human activity led to extreme wildfires in Brazil. In this study, fire activity and air quality data, satellite imagery and modelled air mass trajectories were analyzed to assess the impact of wildfires on air quality in the two largest Brazilian metropolitan areas. In the case of the Metropolitan Area of São Paulo, correlation analysis and air mass trajectory modelling showed that fire events in the north of the state, as well as in the Cerrado and Pantanal, may contribute to high $PM_{2.5}$ levels, in unfavorable meteorological conditions characterized by air stagnation. Air transport simulations showed that pollution from wildfires in the Pantanal, Cerrado and São Paulo state does not affect the air quality in the Metropolitan Region of Rio de Janeiro, but unfavorable conditions, such as severe droughts, high temperatures and air stagnation lead to wildfires, particularly in the mountainous regions, and these are correlated with high $PM_{2.5}$ levels. In conclusion, wildfires not only impacted the burned areas but also the neighboring cities and the two principal metropolitan areas of Brazil, where $PM_{2.5}$ concentrations exceeded the levels stipulated by national standards and the WHO recommendations.

Keywords: wildfires; air quality; particulate matter; smoke plumes; Brazil.

1. Introduction

In comparison with the past historical data provided by the National Institute for Spatial Research (INPE),[1] the number of wildfires in Brazil, and the rest of South America, in 2024, was the highest in the last 14 years. In Brazil, 278299 were reported (54.4% of the total wildfires in South America), in comparison to 189901 and 136139 in 2023 and 2025, respectively. This value is 28% higher than the median value for the period 1998-2025. In 2024, the Amazon rainforest, the Cerrado (a tropical savanna) and the Atlantic rainforest (known as *Mata Atlântica*) accounted for 50.5, 29.3 and 7.7% of the wildfire hotspots in Brazil, respectively.[1] These wildfires were even more severe than the events of 2020 which, with 222796 wildfires, was regarded as the most catastrophic fire season of the last two decades and caused the destruction of approximately a third of the Pantanal wetlands.[2,3] When considering all the historical data (since 1998) the highest value was registered in 2007 (393915) and the lower in 2000 (101530).[1]

The worst drought in the last 44 years was experienced in 2024, with several areas (mainly in the States of Mato Grosso and Minas Gerais) having more than 12 months without rain. In September 2024, more than 290 municipalities in the north and central-west of Brazil (the Amazon, Cerrado and Atlantic Rain Forest biomes) were affected by severe drought.[4] However, neither this serious condition, nor the high temperatures, winds, and relatively low humidity are enough to explain the occurrence of wildfires. Other contributory factors are land use, deforestation, the use of fire to clear lands (through slash-and-burn methods) and human activity (i.e. fires caused deliberately). In fact, as found by Cobelo *et al.*,[5] in a study covering 16 years (2003-2018), the type of land cover and use is correlated with the extent of the wildfire penalty. The authors also found that these events increased the levels of air pollution and health risks.

Similar conclusions were reached in other recent studies,[2,3,6] where the effects of forest wildfires and sugarcane burning were assessed in 2020-2021. Owing to smoke plume dispersion, the effects of fires can go beyond a local scale

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and may impact urban areas placed hundreds of kilometers away.[7]

Wildfires are linked to several environmental and health hazards, including air pollution, financial losses, water resources, climate change, morbidity and mortality risk factors. Catastrophic events in the last decade, such as the 2024 fires were a serious threat to climate, biodiversity, air quality and human health.

Fine particulate matter ($PM_{2.5}$), that is particles with an aerodynamic diameter equal to or less than 2.5 μm, is the main pollutant caused by wildfires, but other criteria pollutants are also emitted and dispersed, such as carbon monoxide, volatile organic compounds (VOC) and nitrogen oxides. The nitrogen oxides ($NO_x = NO + NO_2$) emitted during these events have an important role in atmospheric chemistry and can also lead to the formation of tropospheric ozone and secondary $PM_{2.5}$.[8,9] Furthermore, NO_x emissions alter the ratio VOC/NO_x, which controls ozone formation and tropospheric regime.[10] The role of wildfires in the ozone balance in forested areas has been fully discussed by Artaxo *et al.*[9] During the rainy months, the natural concentrations of CO, VOC, NO_x are low in comparison to urban areas and O_3 levels are < 15 ppb. Wildfires lead to NO_x concentrations similar to urbanized areas, CO values up to 8000 ppb and O_3 concentrations as high as 100 ppb.[9] Satellite data obtained in Eastern Amazon and Cerrado, have also shown that vegetation fires lead to enhancement in NO_x and tropospheric ozone concentrations, which could lead to damage to vegetation and a reduction in photosynthesis and, also, to changes in the biogeochemical cycles of nitrogen and phosphorus.[8] The impact of smoke plums from forest wildfires and sugar cane harvest burning in the interior of the State of São Paulo has been studied by Souto-Oliveira *et al*. and showed that these events increase particulate matter, CO_2 and greenhouse gases in the metropolitan areas of the State.[3] The impact on ozone concentrations is difficult to assess with the available information since the processes of ozone formation and reactions is complex, non-linear and depends on concentrations, VOC/NO_x ratios, VOC speciation, transport and meteorological conditions.[10]

The health hazards of aerosols and gases resulting from biomass burning and wildfires have been studied by other authors and include neonatal morbidity, as well as respiratory and cardiovascular diseases.[11] Short-term exposure is linked to an increased risk of hospital admissions (respiratory, cardiovascular and all-cause), mainly among children and the elderly (over 80 years old).[12] Mother's exposure to wildfire-related air pollution during pregnancy, especially during the first and the third trimester, may cause low birth weight.[13] In 2024, Gao *et al*.,[11] published the first study that quantified the long-term effects of wildfire-related $PM_{2.5}$ emissions to cause-specific cardiovascular mortality in Brazil and found that, during 2010-2018, the proportion of cardiovascular deaths of 17.77 out of every 100,000 people could be attributed to this cause.[11]

The main goal of this study is to analyze the fire activity data provided by INPE and air quality data ($PM_{2.5}$ and CO concentrations) provided by ground monitoring stations, satellite imagery and air mass trajectory modelling to assess the impact of wildfires on air quality (especially particulate matter concentrations) in the two largest Brazilian metropolitan areas.

2. Materials and Methods

2.1. Studied areas

The studied areas are shown in Figures S1a and S1b (Supplementary Information): the Metropolitan Area of São Paulo (MASP) and the Metropolitan Region of Rio de Janeiro (MRRJ), both in the south-east region of Brazil as well as the areas affected by wildfires in 2024 in the States of São Paulo (Ribeirão Preto and São José do Rio Preto) and Rio de Janeiro (Campos dos Goytacazes).

2.2. Urban areas

The MASP with an area of 7,946 km^2, consists of 39 municipalities, within the State of São Paulo, and has more than 21 million inhabitants, and is thus the largest urban agglomeration in South America. It is located on a plateau (Paulistano Plateau) and, as described by De Lima and Rueda,[14] the urban area of São Paulo stretches over a sedimentary basin with altitudes ranging from 918 to 800 meters above sea-level. According to the Koeppen climate classification, its climate is in transition between Cwa (with a dry period) and AF (permanently humid). The Serra do Mar State Park is one of the largest remaining areas of continuous Atlantic Rain Forest and stretches from the border or the State of Rio de Janeiro to the southern part of São Paulo.

Ribeirão Preto, in the north of the State of São Paulo, is an important productor of sugarcane as well as other crops (pastures, maize, peanut and soybean). In São José do Rio Preto, also in the north of the State, the main economical sectors are services, industry and agricultural activities (sugarcane, rubber, orange and maize). In 2024 both cities were affected by severe wildfires.[1]

The MRRJ has been described in several recent articles.[15] It consists of 22 municipalities, with an area of 8,326 km^2 and a population of approximately 13.5 million inhabitants, and is the third largest metropolitan area in South America. It is located on the shores of the Atlantic Ocean and more

than 35% of its surface is covered by preserved Atlantic rainforest, which includes the Tijuca Forest (maximum altitude 1,022 meters), the Pedra Branca park with the Pedra Branca Massif (1,024 meters), the highest point of the city, and the Gericinó-Mendanha park. These urban forests and the ocean play an important role in air mass circulation.[16] The climate is Aw (Atlantic tropical) with a dry season from April to September.

Campos dos Goytacazes, in the northern area of the State of Rio de Janeiro, is the largest city outside the MRRJ, with economical activities based on oil extraction. It is the largest soybean producer in the state's interior and an important producer of sugarcane.

2.3. Non-urban areas

The non-urban areas are briefly described because their characteristics determine how wildfires are initiated and propagated. According to the Ministry of Environment and Climate Change (Ministério do Meio Ambiente e Mudança do Clima, MMA), Brazil has six biomes: Amazônia (Amazon rainforest), Cerrado (central Brazilian savanna), Atlantic rainforest (Mata Atlântica), Caatinga, Pampa and Pantanal.[17,18] These biomes have been fully described,[19,20] and classified by Pivello *et al*.,[7] as fire-dependent (Cerrado, Pantanal e Pampa), fire-sensitive (Amazon and Atlantic rainforests) and fire-independent (Caatinga), in accordance with the criteria drawn up by Hardesty *et al*.[21,22] In 2024, the most affected areas were the Amazon forest, Cerrado, Atlantic rainforest and Pantanal, which accounted for approximately 90% of the wildfire hotspots.[1]

In short, 60% of the Amazon rainforest is located in north and central-west Brazil (occupying more than 4 million km^2) while the remaining forest extends through Bolivia, Peru, Ecuador, Colombia, Venezuela, and the Guianas. It is the largest humid tropical forest in the world and the predominant vegetation is flooded and tall lowland forest (terra firme).[19] As shown in recent studies, the Amazon forest carbon sink capacity is declining, as it is affected by climate change and land use (deforestation, including illegal deforestation, and burnt areas).[23] The Cerrado, the second bioma regarding its extension, occupying approximately 23% of Brazilian territory. It comprises a mosaic pattern of vegetation, predominantly grassland with woodland features and is considered the largest tropical savanna on Earth. About 50% of its natural vegetation has been lost as a result of agriculture and livestock farming.[20] The Atlantic rainforest originally occupied 13% of the Brazilian territory and was the second largest tropical forest in South America, but, since 1500, it has been devastated and only 8% of its area still remains as native fragments. It houses approximately 145 million people and the two major metropolitan areas in Brazil (MASP and MRRJ). The Pantanal, an area with flooded grasslands in central-west Brazil, comprises 1.8% of its territory and is considered to be the world's largest continuous stretch of wetlands.[2] Both the Atlantic Forest and Cerrado are regarded as hotspots for the conservation of biodiversity.[24]

2.4. Data collection and modeling

$PM_{2.5}$ concentrations were determined by automated monitoring stations operated by the São Paulo State Environmental Protection Agency (CETESB, Companhia Ambiental do Estado de São Paulo) and the Rio de Janeiro State Environmental Institute (INEA, Instituto Estadual do Ambiente). Data were obtained in compliance with Brazilian legislation, and with the aid of devices recommended by the Environmental Technical Guide (ETG) published by the Brazilian Ministry of Environment,[25] and the equivalent EQPM-0308-170 Method.[26] These data are available as 1-hour means at the CETESB and INEA platforms for the management of air quality.[27,28] Considering the recommendations of the ETG,[25] data were considered representative for the calculations when the following conditions were met: 3/4 of the valid data for a 1-hour average and 2/3 of the valid data for 24-hour averages. Data were compilated from 1 June to 30 September, that is during the drought months. 24-hour averages were calculated for this period of time on the basis of ETG guide.

The monitoring stations in the State of São Paulo were: Ibirapuera, Pedro II, Osasco, Santana e Ribeirão Preto. Ibirapuera and Pedro II are representative locations of the city of São Paulo, while Osasco e Santana are representative of the other municipalities within the MASP.[27] In the State of Rio de Janeiro, the stations were: Manguinhos, Largo do Bodegão e Campos dos Goytacazes. In the city of Rio de Janeiro, the only available data were for Adalgiza Nery e Largo do Bodegão stations (both in Santa Cruz) and Manguinhos.[28] Other stations were initially investigated but were not considered in this study because did not provide additional information.

Fire activity throughout Brazil is monitored by INPE.[1] Daily and monthly fire spots have been available since 1998, classified by region, biome and State. INPE data are obtained with the aid of cutting-edge technology, such as the Fire Panel, which integrates information from several satellites to monitor fires and prioritize fire-fighting actions. The main satellites are the WFI sensors of CBERS-4 and CEBERS-4A and the Amazônia-1 satellite. These results are combined with images of Landsat-8, Landsat-9, Sentinel -2, NOAA-18, NOAA-19, Metop B and C, Terra and Aqua and geo-stationary satellites, such as GOES-16 and Meteosat-11.[1]

Data were analyzed and arranged by means of R language

scripts,[29] and the Openair package, which are currently recommended for air quality analysis.[30] The investigation of possible associations between $PM_{2.5}$ levels, meteorological variables and burning indicators was conducted using Spearman's correlation analysis, a non-parametric method for analyzing data that do not follow a normal distribution, via a custom-written script in R language.

Trajectory modeling was performed with the National Oceanographic and Atmospheric Administration model HYSPLIT, which was run interactively on the READY web site using meteorological archival data and the Global Data Assimilation System (GDAS 1.0) with a 0.25-degree resolution.[31] HYSPLIT is well documented and is one of the most widely used atmospheric transport and dispersion models for both backward and forward trajectories. In this study the archive dispersion option for unknown material (generic mass with duration > 24 h) was used, considering a total duration of 72 hours and an averaging period and output interval of 1 hour.

3. Results and Discussion

3.1. Wildfires in 2024

In 2007 and 2010 more than 300,000 wildfires destroyed approximately 6.9% and 6.0%, of the Brazilian territory respectively. In 2020, wildfires in the Pantanal reached an unprecedented magnitude burning approximately 26.4% of this biome, while the total burned area in Brazil was 3.6%. In 2024, the total number of wildfires, detected by the observation satellites (Aqua and Terra), was 278,299 and caused the destruction of 18.1%, 13.2%, 11.9%, 4.4% and 3.9% of the Pantanal, Caatinga, Cerrado, Atlantic rainforest and Amazonia, respectively.[1] The total fire burned area comprised 303,732 km^2 (7.0% of the Brazilian territory), the second-largest area in the past 40 years.[32] August and September 2024 were the most critical months, in terms of the number of fire events and their intensity, which is indicated through the Fire Radiative Power (FRP) values, that is the rate of radiant energy emitted by fire (in megawatts) (see Table S1, (Supplementary Information).

3.2. São Paulo State and MASP

The main fire events in the interior of São Paulo State can be attributed to agricultural activities, especially sugarcane cultivation,[33] and in 2024 occurred in the period 22-24 August in the vicinity of Ribeirão Preto and São José do Rio Preto (in the north of the State, approximately 300 km from MASP). The 24-hour $PM_{2.5}$ concentrations (measured by CETESB at the monitoring station of Ribeirão Preto), were approximately 53, 250 and 186 μg m^{-3} on 23, 24 and 25 August, respectively. As described by Campos,[33] on 24 August, the 1-hour mean $PM_{2.5}$ concentration reached 1,392 μg m^{-3}. Driven by a combination of local fire events, severe drought, low relative humidity (approximately 20%), regional transport of pollutants, and strong wind gusts, solar radiation dropped drastically to 10 W m^{-2} at 16:30 h (at midday the value was 717 W m^{-2}), resulting in complete darkness by 17:00 h.[33] 24-hour carbon monoxide concentrations were 2 and 3.5 ppm, on 24 and 25 August, respectively, in comparison with approximately 1 ppm on the same days of 2023.[27] In Figures S2a and S2b (Supplementary Information), satellite images show $PM_{2.5}$ and CO concentrations, respectively, and the plumes from Amazonia, the Pantanal and Cerrado.

This unprecedent extreme event was widely discussed in the media and social networks and led to the cancellation of school classes and sporting activities, the closure of companies and highways and an increase in hospitalizations. On 24 August, the number of hospital appointments in the public health service was about 60% higher than on a normal day. In August 2024, the number of hospital admissions (caused by respiratory diseases (Chapter CID 10, X)) in that region (Ribeirão Preto and São José do Rio Preto) was 13 and 27% higher than in 2023 and 2022, respectively. In September 2024, they were 24 and 31% higher than in the same months of 2023 and 2022, respectively.[34] Furthermore, according to the Ribeirão Preto Municipal Health Secretary, in 2024 there was an increase in the number of deaths related to respiratory diseases (Chapter CID 10, X) of 126% and 117% compared with the corresponding figures for 2023 and 2022.[35]

According to the CETESB monitoring station at Ribeirão Preto, in August and September, between 74% and 100% of the 24-hour mean concentrations were higher than 15 μg m^{-3}, the final National Air Quality Standard (NAQs) established by CONAMA in 2024, [36] which is based on the 2021 WHO Air Quality Guidelines (WHO AQGs, 2021).[37] Furthermore, in August and September several 24-hour $PM_{2.5}$ concentrations were also higher than the less restrictive value (25 μg m^{-3}) of the NAQs established in 2018.[38] These values show that the levels were higher than the NAQs final target and the recommendations of the WHO. Nevertheless, in August and September 2024, the legally binding threshold was strictly the Intermediate Standard 1 (PI-1), which establishes a 24-hour limit of 60 μg m^{-3}, certainly a high value in comparison to WHO recommendations. The values for June-September 2023 and 2024 are shown in Figure S3, (Supplementary Material).[27]

The 24-hour $PM_{2.5}$ concentrations measured in July-September in two MASP monitoring stations (Ibirapuera and Pedro II Park) are shown in Figures 1a e 1b, respectively.

Data for Santana and Osasco are displayed in Figures S4 and S5 (Supplementary Information), respectively. Data for 2023 are shown for purposes of comparison.

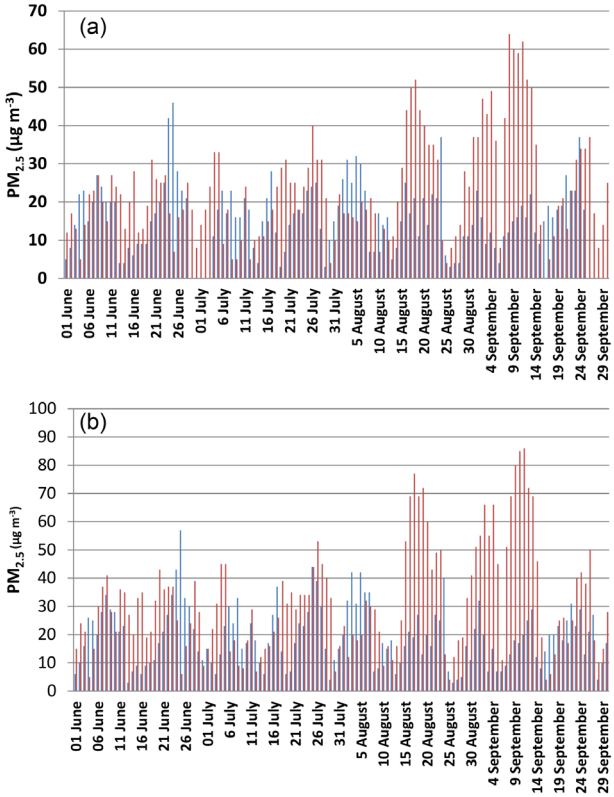


Figure 1. (a) 24-hour $PM_{2.5}$ concentrations in Ibirapuera, for the period June-September 2023 (blue) and 2024 (red);[27] (b) 24-hour $PM_{2.5}$ concentrations in Pedro II Park, for the period June-September 2023 (blue) and 2024 (red)[27]

During the 22-24 August fire events in the north of the State, $PM_{2.5}$ concentrations were higher than the WHO recommendations but lower than other levels recorded in August-September, which suggests that fire events within the State are not the only explanation for the high levels of fine particulate matter. Clearly, high $PM_{2.5}$ concentrations may be also caused by other events, such as local emissions, transport of pollutants from fires in other regions, and meteorological parameters. In Figure S6 (Supplementary Information), the Spearman's correlation analysis, for the period June-September 2024, is shown and takes account of the following parameters: the 24-hour $PM_{2.5}$ concentrations recorded in Ibirapuera, Pedro II Park, Osasco and Santana stations,[27] the mean FRP in the Cerrado, Pantanal and São Paulo State,[1] temperature, relative humidity and thermal inversion.[27] 24-hour $PM_{2.5}$ concentrations in the four stations are highly correlated (factor >93), as well as the concentrations and meteorological parameters (factor >65). The correlation with fires in São Paulo State is intermediate, while with fires in the Cerrado and Pantanal is relatively low (factor 30).

When specific high concentrations events are considered, the correlation with wildfires (FRP) is higher, especially with the Cerrado. In order to exemplify this fact, the correlation for the period 06-16 September is shown in Figure 2. To confirm these results, the trajectory of air masses from Chapada dos Veadeiros (the most impacted area in Cerrado), initiating on 10 September is shown in Figure 3 (72 hours). The model shows that these air masses arrived at MASP in approximately two days (indicated in Figure 2 as "lag 2") also contribute to $PM_{2.5}$ levels.

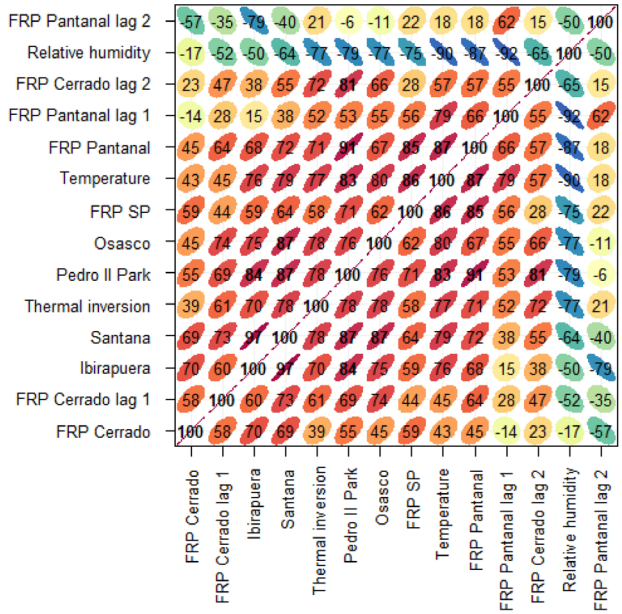


Figure 2. The correlation analysis for the period 06-16 September 2024 is shown considering: 24-hour $PM_{2.5}$ concentrations that were recorded in Ibirapuera, Pedro II Park, Osasco and Santana stations,[27] the mean FRP in Cerrado, Pantanal and São Paulo State,[1] temperature, relative humidity and thermal inversion.[27] Lag 1 and lag 2 refers to one and two days after particular fire events

Correlation analysis and air masses modelling show that, in spite of the local contributions to particulate matter emissions, fire events in the north of the state (Ribeirão Preto and São José do Rio Preto) as well as in the Cerrado and Pantanal, associated to unfavorable meteorological conditions and air stagnation are also related to high $PM_{2.5}$ levels and event days when the WHO and Brazilian standards were exceeded. Clearly, the number of days when the NAQs and the WHO air quality guidelines were exceeded gives rise to a worrying situation since, as previously mentioned, the high short-term exposure to $PM_{2.5}$ could cause adverse effects to public health. According to the Brazilian Public Unified Health System (DATASUS), in August and September 2024, the number of hospital admissions caused by respiratory diseases (Chapter CID 10, X) were 4% and 7.7% higher than in the corresponding months of 2023.[34]

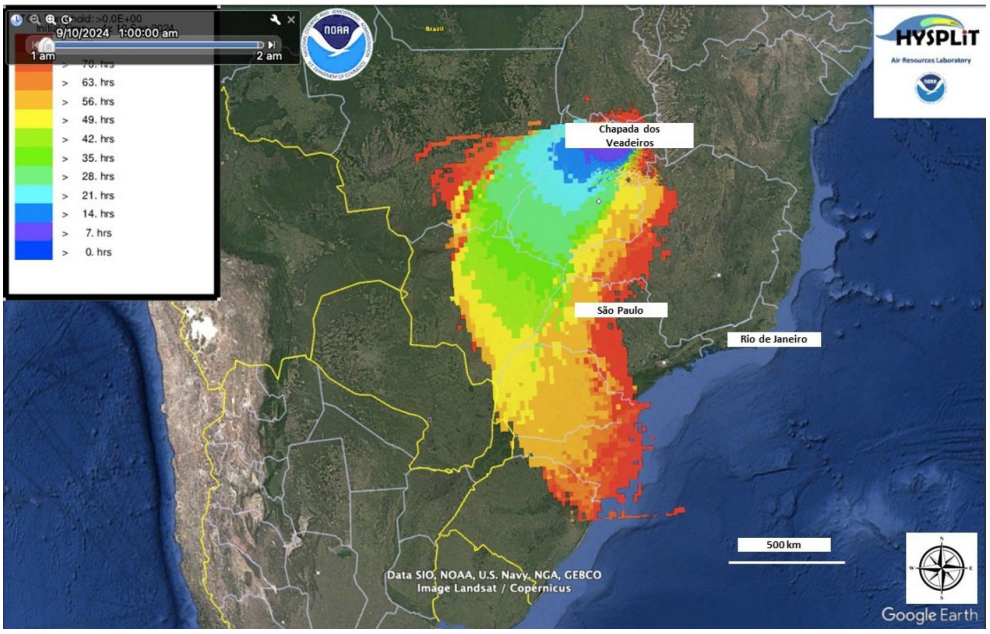


Figure 3. HYSPLIT forward dispersion analysis of air masses from the municipality of Cachoeira Simão Correia in Chapada dos Veadeiros (the most seriously affected area in Cerrado during September), beginning on 10 September 2024. Air masses were released at soil level, using the coordinates 14º 08' S and 47º 31' W as initial point [31]

3.3. Rio de Janeiro State and MRRJ

The main fire events in Rio de Janeiro State in 2024 occurred in September (Figure S7, Supplementary Information), when the number of fire spots was 3.5 higher than in September 2023. These were in the northern agricultural area (Campos dos Goytacazes, São José de Ubá, and Italva), the mountainous region (Duas Barras, Teresópolis, Petrópolis, Nova Friburgo, Valença, Volta Redonda and Resende) and the conservation areas in the MRRJ (Tijuca and Pedra Branca Parks). In the first two weeks of September, more than 340 fire spots were detected and, on 14 September, wildfires were reported in 15 Conservation Units. Several of these events were the result of anthropogenic ignitions and were favored by atypical meteorological conditions and droughts. On 14 September, the State Government closed 40 Conservation Units,[39] and set up a crisis management group. The main affected areas, in the vicinity of the MRRJ, are shown in Figure S8 (Supplementary Information).

The 24-hour $PM_{2.5}$ concentrations which were recorded in the period from July to September in the monitoring station of Largo do Bodegão, in the District of Santa Cruz (western zone of Rio de Janeiro), are shown in Figure 4. Data for Manguinhos (northern zone) are displayed in Figure S9 (Supplementary Information). Data for 2023 are shown for purposes of comparison. In September, the 24-hour $PM_{2.5}$ levels determined in Santa Cruz and Manguinhos were > 15 μg m^{-3} in 87% and 50% of the days, respectively (the WHO recommended value) but lower than the Intermediate Standard 1 (PI-1) valid in 2024. The western zone is relatively open countryside, with low hills, which allows the arrival of air masses from the region of Seropédica (north) where industrial, agricultural and extractive activities are carried out and also from the area of the Port of Itaguai (in the west) which is a center of industry and commercial activities. Also, as shown in Figure S8, Seropedica was heavily affected by wildfires. In contrast, Manguinhos has a poorest air circulation and receives air masses from the petrochemical area of Duque de Caxias and local vehicular emissions, but air masses from Seropedica are obstructed by the mountainous region (mainly Gericinó Mendanha).

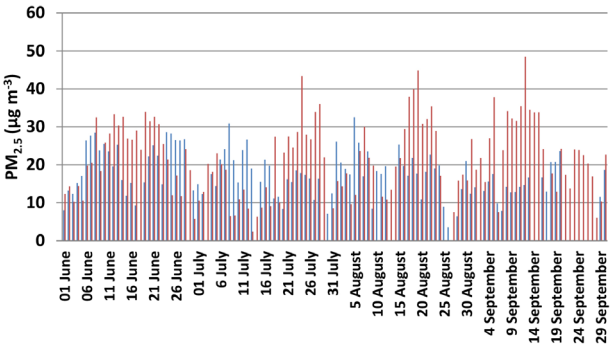


Figure 4. 24-hour $PM_{2.5}$ concentrations in Largo do Bodegão, Santa Cruz (city of Rio de Janeiro) for the period June-September 2023 (blue) and 2024 (red)[28]

The correlation analysis for the event in 09-18 September 2024 is shown, in Figure 5, and includes: 24-hour $PM_{2.5}$ concentrations determined in two monitoring stations of the MRRJ,[28] the mean FRP in Rio de Janeiro State (INPE,

2025), temperature and relative humidity.[28] The 24-hour $PM_{2.5}$ concentrations in the two stations are highly correlated (factor 86), as well as concentrations and meteorological parameters, number of fire spots and FRP (factor >85).

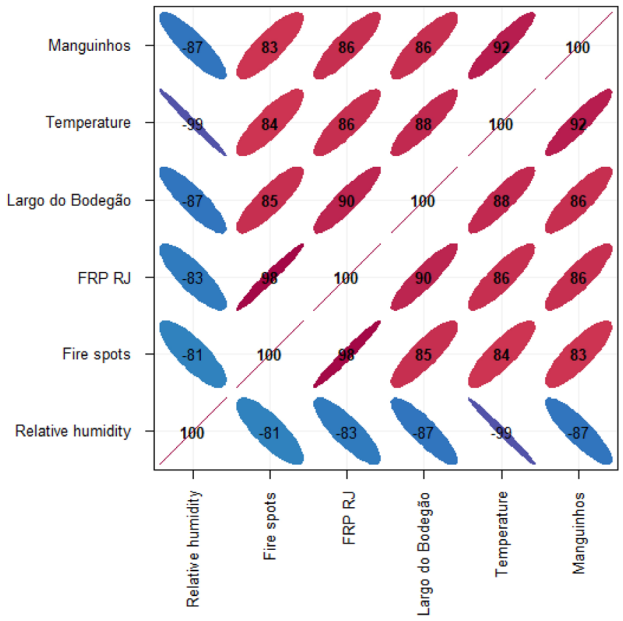


Figure 5. Correlation analysis for the period 09-18 September 2024, including: 24-hour $PM_{2.5}$ concentrations determined in two monitoring stations at the MRRJ (Largo de Bodegão/Santa Cruz and Manguinhos),[28] the mean FRP in Rio de Janeiro State,[1] temperature and relative humidity[28]

The air masses trajectories, calculated with HYSPLIT, showed that, in general, the particulate matter emitted by wildfires in the north of the State does not reach the MRRJ since it is dispersed to the Atlantic Ocean. But air masses (Figure 6) caused by wildfires in the vicinity of the MRRJ, were transported to the south (as simulated for 23 September 2024), when severe fires were detected in Seropedica (see Figure S8, Supplementary Information) and a 24-hour $PM_{2.5}$ concentration of 25 μg m^{-3} was determined in Santa Cruz.

Fires in July and August 2024 were approximately 1.5 and 2 times higher than in the same months of 2023. In Figure S10 (Supplementary Material), the number of reported fires and 24-hour $PM_{2.5}$ concentrations determined at Largo do Bodegão (Santa Cruz, MRRJ) are shown and suggest a strong correlation.[1,28]

24-hour $PM_{2.5}$ concentrations in the MRRJ are lower than values determined in MASP, but are also high when compared with values recommended in the NAQs and WHO guidelines.[36,37] The number of days with $PM_{2.5}$ concentrations > 25 μg m^{-3} were 16, 9, 13, 17 in June, July, August and September 2024. Correlation analysis (Figure 5) indicates that high particulate matter levels are found when there are high temperatures and low relative humidity. Air transport simulations showed that the pollutants resulting from the Pantanal, Cerrado and São Paulo wildfires, do not affect the air quality in the MRRJ. But adverse conditions, such as severe droughts, high temperatures and air stagnation favors wildfires, especially in the mountainous regions and Conservation Units, which are correlated with high $PM_{2.5}$ levels. Most of these fires are of anthropogenic origin and caused by criminal activities.

In conclusion, this study shows that 2024 wildfires, notably in the Atlantic Rainforest, have affected not only the burnt areas but also the two main Brazilian cities (MASP and MRRJ), where $PM_{2.5}$ concentrations exceeded national final standards and WHO recommendations.[36,37] Fires in the

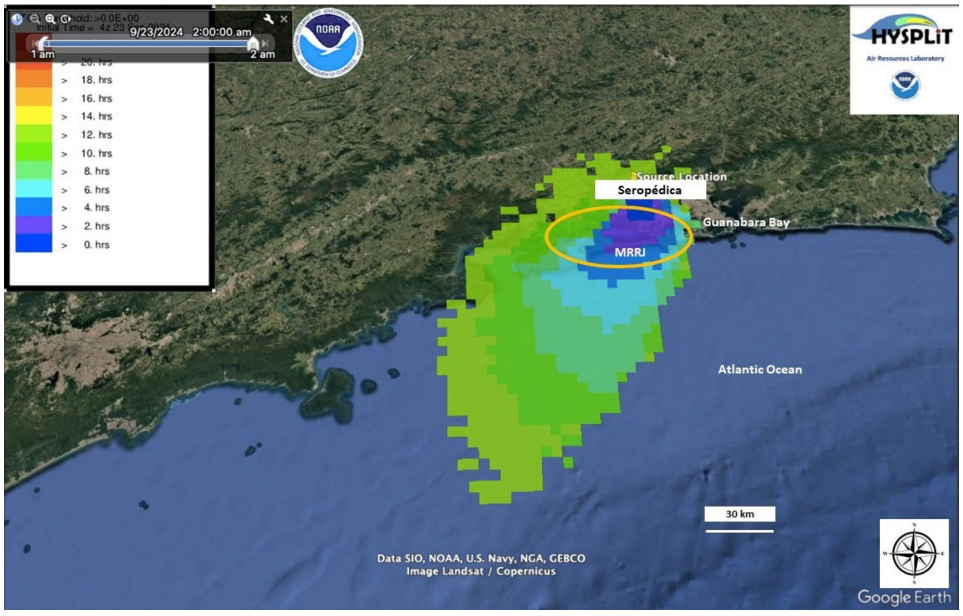


Figure 6. HYSPLIT forward dispersion analysis of air masses from Seropédica (situated 75 km north of the MRRJ), beginning on 23 September 2024[31]

Pantanal and Cerrado also affected the State of São Paulo. These fires were generally caused by criminal activity and, in 2024, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) issued citations against hundreds of people.

As recently discussed,[40,41] the frequency and intensity of drought and wildfires globally have increasingly been driven by climate change. Land use changes and harmful human activities also add to the risk of extreme events, especially in tropical forests.[42] In 2024, catastrophic wildfires in Brazil and other South American countries (in Bolivia, Venezuela, Peru, Guiana and Ecuador) destroyed an area of unprecedented size, exposed millions of its inhabitants to hazardous air quality and had an adverse effect on biodiversity and ecosystem services.[40] Moreover, future climate change is likely to create the suitable conditions for more extreme events to occur. In light of this, the combined efforts of the academic community, government and the whole of society are required to combat this trend and protect the Brazilian biomes and health of the public.

4. Conclusions

In the winter of 2024, the number of fire outbreaks was higher than that recorded in the same period in any of the last 14 years. Adverse conditions, particularly severe drought, high temperatures and atmospheric stagnation, associated to human activities (such as the use of fire for pasture renewal, deforestation and criminal activities) led to the destruction of vast areas of Amazonia (the most seriously affected biome), as well as the Pantanal, Cerrado and the Atlantic rainforest. The effects of fires and air pollution know no borders, and smoke from fires has affected both nearby areas and distant metropolitan regions. The results of this study showed that the MASP is affected by fires in the north of the State as well as the Pantanal and Cerrado. The MRRJ is mainly affected by fires in the mountain area which had a significant impact on the scarce forest remnants within the biome.

Wildfires not only destroy biodiversity, aggravate air pollution and pose a risk to human health, but also worsen climate change by releasing significant amounts of greenhouse gases into the atmosphere.

Supplementary Information

Supplementary figures (Figures S1-S10) are available free of charge at https://rvq.sbq.org.br/pdf/AR2026-5223- MS.

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