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Evidence of the consequences of the prolonged fire season on air quality and public health from 2024 São Paulo (Brazil) data

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Over the last decade, the number of forest fires in Brazil has been increasing continuously. In 2024, the number of forest fires in São Paulo state reached unprecedented levels. This phenomenon, combined with unfavorable conditions for pollutant concentrations, given temperature and precipitation anomalies, resulted in high concentrations of pollutants for several weeks, mainly affecting the number of hospitalizations of the most vulnerable age groups, children (due to respiratory diseases) and older adults (due to cerebrovascular diseases) in the city of São Paulo. The Incidence Rate Ratio calculations demonstrate how different age groups are differently affected by changes in pollutant concentrations and meteorological variables, so that air temperature, relative humidity, concentration of Particulate Matter, SO_2, NO_2, and O_3 are the main variables that affect hospitalizations by respiratory, cerebrovascular or cardiovascular diseases.

Keywords Brazilian forest fires, Air pollution, Respiratory diseases, Cerebrovascular diseases, Cardiovascular diseases

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In the last decades, the frequency and extent of forest fires have increased dramatically worldwide[1]. Large-scale wildfires were observed in California (USA) in 2008[2], Colorado (USA)[3] and Valencia (Spain)[4] in 2012, Canada[5] and Portugal[6] in 2017, and Southeast Australia in 2019–20[7]. Anthropogenic activities, such as deforestation and pasture renovation or clearing, combined with extreme weather conditions like droughts and high air temperatures, have contributed to the occurrence and rapid spread of forest fires on an unprecedented scale and duration[8,9]. This combination of wildfires, particularly in tropical regions, unsustainable land use, and climate change, has caused a reinforcing effect due to a reduction in the Earth's capacity to sink CO_2, disrupting the regulation of this greenhouse gas. As a result, the reinforcing effect leads to increased warming, which is one of the factors for igniting new fire outbreaks[10].

Over the last decade, Brazil has attracted significant attention due to the large number and extent of forest fires, ranking first in the number of wildfires in South America[11]. Among the various biomes in this country, the Amazon and the Atlantic Forest (the predominant biome in the state of São Paulo) deserve special attention, as both can be classified as fire-sensitive because fire harms their biodiversity[12]. Therefore, at these biomes, only adverse conditions related to extreme droughts make them more vulnerable to fire[13]. However, climate changes have caused anomalies in rainfall patterns, intensifying droughts in tropical and subtropical areas, particularly during severe El Niño/Southern Oscillation (ENSO) events[14–16] and due to effects of Atlantic Meridional Overturning Circulation (AMOC) weakening[17]. When combined with unsustainable land use, such anomalies can increase the frequency and intensity of heat waves, providing more ignition sources for fires and lengthening the wildfire season. For instance, in 2020, over 312,140 km^2 of the Brazilian territory was burned, with 46.3% and 28.6% of these fires concentrated in the Amazon and Cerrado biomes, respectively[18]. This same year, the Pantanal was also devastated by a severe fire, which affected about a third of its total area (around 40,606 km^2)[19].

Forest fires harm the local fauna and flora and directly impact public health through atmospheric pollution. Their harmful effects can range from eye irritation and corneal abrasions in nearby populations to a significant increase in hospitalizations and deaths caused by respiratory and cardiovascular diseases, even in regions up to 1000 km away[7].

Wildfire events can significantly contribute to an increase in the concentration of carbon monoxide (CO) (generally confined to regions directly affected by the fire), methane (CH_4), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and particulate matter (PM), particularly fine and ultrafine particles. These particles can travel long distances, causing harmful effects even in areas far from the fire's origin[20,21]. Compared to urban PM, wildfire-generated PM contains higher levels of oxidative potential (e.g., oxygenated PAHs and quinones) and proinflammatory components (e.g., aldehydes and NOx).

The exposure to wildfire smoke can result in respiratory (bronchitis, pneumonia, chronic obstructive pulmonary disease [COPD]), cardiovascular diseases (hypertension, heart stroke), and allergic and immunological disorders (Atopic dermatitis, Allergic rhinitis, and Asthma)[22].

CO can form carboxyhemoglobin when it enters the human body. This compound impairs oxygen transport and can cause hypoxia, as well as having long-term toxic consequences for the body's organs and tissues. Furthermore, CO can disrupt intracellular respiratory processes, resulting in cellular hypoxia. Carbon oxides bound to intracellular macromolecules have toxic effects on all body tissues[23,24]. NO_x, mainly from wildfire smoke, can cause coughing and inflammation of airways, favoring the prevalence of asthma and COPD[25,26]. VOCs can be composed of several elements that are harmful to human health (eg, acrolein, benzene, formaldehyde, toluene, etc.). In addition, they can react with hazardous compounds, like peroxyacetyl nitrate (PAN), resulting in a compound that favors the eyes, nose, and throat irritation[27,28]. Prolonged exposure to high concentrations of O_3 contributes to respiratory and cardiovascular diseases, especially in the most vulnerable populations[29]. SO_2 can cause irritation and inflammation of the airways, affecting the respiratory system[30]. The exposure to high PM concentrations affects the cardiovascular, dermal, digestive, immune, nervous, respiratory, and reproductive systems[29]. However, compared to urban PM, wildfire-generated PM contains higher levels of oxidative potential (e.g., oxygenated PAHs and quinones) and proinflammatory components (e.g., aldehydes and NOx).

Furthermore, it is essential to highlight that as PM ages, its chemical composition changes, and its oxidative potential increases. As a result, PM generated by wildfires can become more toxic to macrophage cells as it travels, eventually reaching urban areas. Additionally, ultra-fine PM can pass through the alveolar membrane and penetrate deeper into the lungs. This can lead to changes in pulmonary responses, potentially affecting airway function and the body's ability to resist viruses and bacteria. Consequently, hospital admissions and emergency visits for respiratory symptoms, mainly for asthma, bronchitis, dyspnea, pneumonia, and COPD symptoms increase significantly[31–36]. In addition, exposure to elevated levels of PM2.5 impairs vascular function, which can contribute to cardio and cerebrovascular diseases[37].

Therefore, although other events, such as dust storms[38], extreme pollen seasons[39] or changes in local emission patterns[40] have been reported in the literature as responsible for the increase in hospital admissions, fire events deserve to be highlighted due to the change that occurs in the toxicity of the particles, making them extremely harmful to the population, especially the most vulnerable one.

Figure S1 summarizes the interactions described above and demonstrates how combining several processes can increase the number of mobility and mortality cases associated with high temperatures and air pollution levels. Based on this scenario, the current study aims to investigate how the increase in the number of forest fires, between January and September 2024 in São Paulo Municipality, combined with atmospheric conditions less favorable to pollutant dispersion, mainly during winter, resulted in a high concentration of atmospheric pollutants, and consequently on variations in the number of hospitalizations by respiratory, cardiovascular, and cerebrovascular diseases.

Results

Wild fires and pollutant concentrations

Figure 1 shows the number of fires and fire foci observed in São Paulo state from January until September 2024 (gray stars), compared to the average values recorded from 2004 to 2023 (red lines). Since January, the observed values have consistently exceeded the historical average several times, with this trend becoming even more concerning during the fire season. On some days, up to 2,000 fires or outbreaks have been recorded. The data observed in 2024 also indicate an extension of the fire season, which historically begins in July and ends in the middle of October. However, more fire events have been observed since January this year. The increasing number of fires can be attributed to extreme drought conditions and high temperatures, recorded in Brazil's southeast, central-west, and north regions in 2024. The figures S2 and S3 illustrate the temperature and precipitation anomalies for August and September, which coincided with the highest number of wildfires and/or fire spots. Both figures show meteorological conditions favorable to fires (higher temperature and reduced precipitation), particularly in the southeast, central-west, and north regions.

The Fig. 2 presents the August and September (Figs. 2a and b, respectively) Ångstrom Matrices[41–43] for São Paulo Municipality. Small particles ($PM_{2.5}$) and black carbon are observed in both months, with the latter detected through its differential Single Scattering Albedo (dSSA). Although black carbon can be produced locally from vehicle emissions, the presence of particles with greater absorption capacity suggests the occurrence of the lensing effect[44]. This process is associated with the aging aerosols transported from other regions, which become coated with secondary organic aerosols. The advection of smoke plumes from fires occurred in rural areas of São Paulo state and Midwest and north regions of Brazil, to São Paulo Municipality, especially during the fire season, has been reported in several previous studies[21,45,46].

This information is complemented by Fig. 3, which shows the daily mean concentration of $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2, and AOD values in São Paulo Municipality. As indicated in Fig. 1, the stars represent values registered from January to September 2024, while the red line shows the historical average value. Historically, higher concentrations of pollutants are observed in São Paulo during the winter months (June, July, and August) due to unfavorable conditions for pollutant dispersion (e.g., low convective boundary layer height, reduced wind speed, and absence of rain). Additionally, the average daily PM concentration often exceeds the national and international recommended daily limits between July and August, primarily due to the high number of biomass burning events, which advects smoke plumes to São Paulo Municipality, combined with the local emissions of air pollutants, as mentioned previously. In 2024, although the observed pattern is quite similar to the historical average PM concentration (Figs. 3a-b), it is evident that since May, the average daily concentrations have largely exceeded the historical average values, with a significant part surpassing the average standard deviation. From August onwards, the concentrations have predominantly remained above the average standard deviation. For $PM_{2.5}$ and PM_{10}, on certain days (23–25 September), the measured values were more than double the average standard deviation values. This pattern of higher values in 2024, compared to the historical time series, is also observed in O_3 (Fig. 3c) and NO_2 (Fig. 3e) (mainly in September).

On the other hand, SO_2 (Fig. 3d) has a predominance of values below the average values, so September is the month with the higher number of days whose daily concentration is close to the average value provided by historical time series. This behavior results from reducing the sulfur content of fossil fuels, both industrial and automotive[47]. The higher AOD values (Fig. 3f) observed in 2024 are primarily due to the combination of adverse

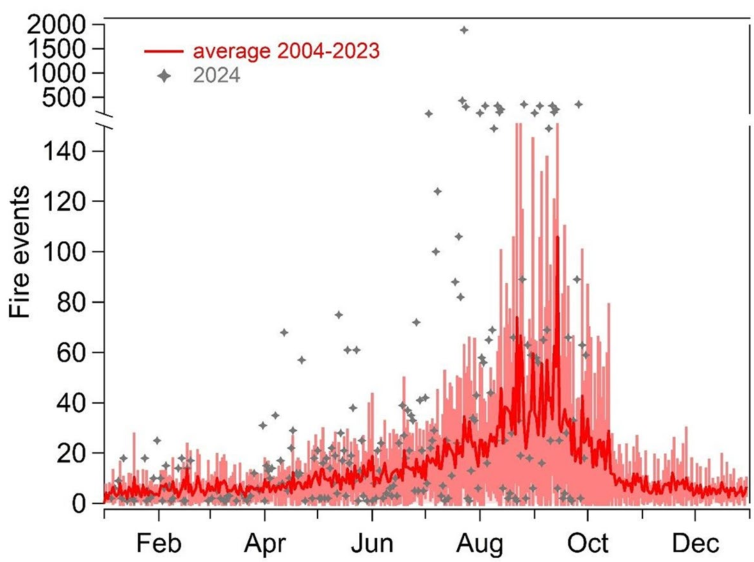

Fig. 1. Number of Fire Events/Fire Forci from 2003 to 2024 in São Paulo state. The red line represents the daily average from 2004 to 2023, and the red shade depicts the standard deviation. The grey markers indicate the daily number of fire events in 2024. Note the change in the scale of fire events to reflect the elevated number in 2024 accurately. Source: https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/.

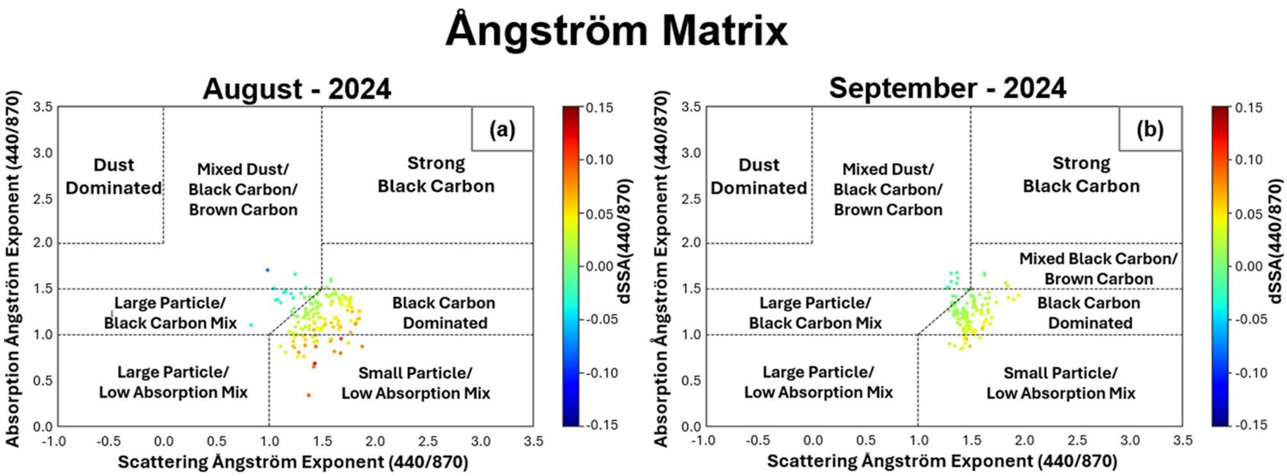

Fig. 2. Ångström Matrix for São Paulo Municipality in 2024 (**a**) august and (**b**) september.

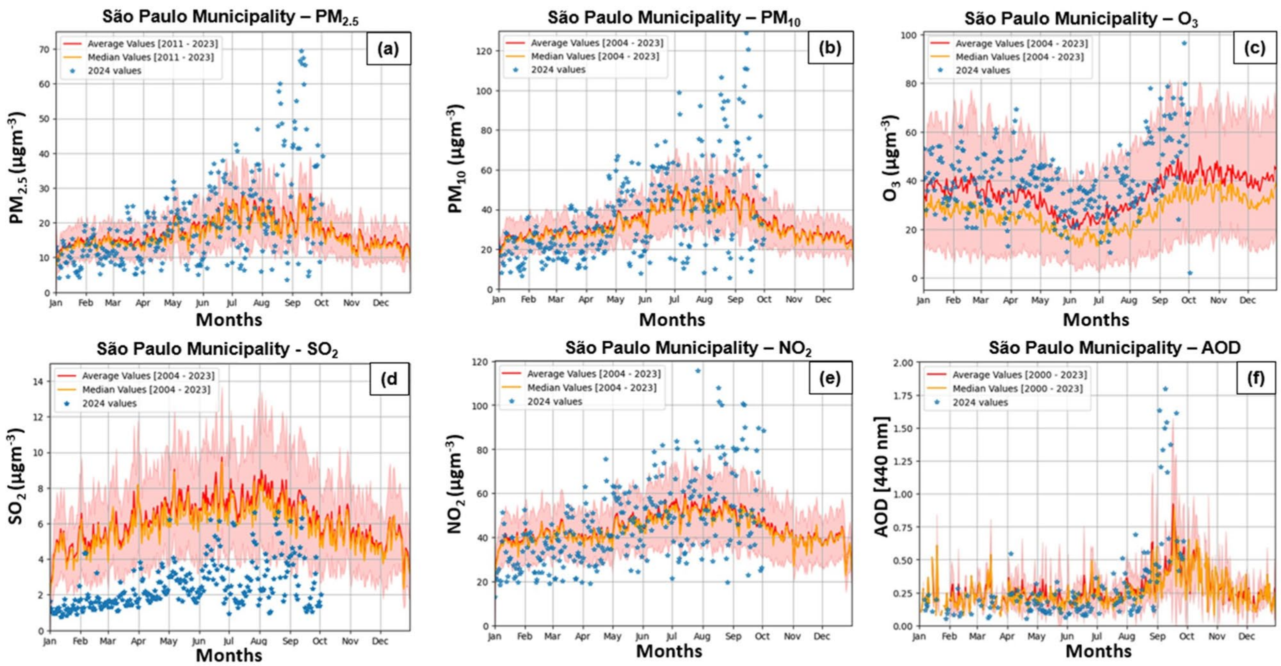

Fig. 3. Average daily concentration of $PM_{2.5}$ (**a**), PM_{10} (**b**), O_3 (**c**), SO_2 (**d**), NO_2 (**e**) and AOD (**f**) at São Paulo municipality.

meteorological conditions (low air relative humidity, absence of rainfall) and wildfires, which together created less favorable conditions for pollutant dispersion, leading to increased concentrations of NO, NO_2, NO_x, and PM. In addition, the figure S4, derived from VIIRS satellite data, presents the Ultra Violet Aerosol Index values in Brazil on 23 September, showing high values (consequently high concentration of aerosols) in the Southeast, Midwest, and Northern regions. Unfortunately, field measurements of chemical compounds were not performed during 2024. Nevertheless, previous field campaigns in the Metropolitan Area of São Paulo have identified the presence of some biomass burning tracers such as levoglucosan, mannosan, and galactosan[48], in the aerosol fine aerosol, in mass concentrations up to 1.2 µg m-3 (levoglucosan) during wintertime[49,50]. The authors concluded that São Paulo is impacted by regional sugarcane crop burning, what was also confirmed by analyzing air mass trajectories from the west and northwest, and by satellite measurements identifying hundreds of daily forest fires across the field campaigns.

Therefore, it can be concluded that the combination of unfavorable atmospheric conditions for the dispersion of pollutants and the increase in the number of fires resulted in higher concentrations of the pollutants shown in Fig. 3.

Variations in hospitalizations due to respiratory, cardiovascular, and cerebrovascular diseases

Figure 4 presents the incidence of respiratory (Fig. 4a), cerebrovascular (Fig. 4b), and cardiovascular (Fig. 4c) diseases recorded in DataSUS for São Paulo Municipality from 2000 to 2024. Respiratory diseases are most prevalent in children, followed by adults, and then older adults. These diseases exhibit seasonality, with a sharp increase at the beginning of autumn (March–May) and a significant reduction during the summer (December-February). From February to September 2024, the number of children diagnosed with respiratory diseases was higher than the average value observed from 2000 to 2023, particularly during the first week of April (302 in 2024 compared to an average of 247 between 2000 and 2023, a 21% increase) and the first week of September (267 cases in 2024 compared to an average of 151 between 2000 and 2023, a 77% increase). In addition, the average number of cases in 2024 (161 ± 70) was higher than the average observed during the same months in 2000–2023 (150 ± 52). The same pattern was observed in older adults (60 ± 14 in 2024 compared to 48 ± 4 from 2000–2023), while the difference in adults was smaller (95 ± 46 during 2024 compared to 94 ± 27 from 2000–2023).

According to data extracted from DataSUS, cerebrovascular diseases in São Paulo (Fig. 4b) primarily affect older adults (101 ± 5 hospitalizations/year), followed by adults (57 ± 3 hospitalizations/year). The number of children diagnosed with these diseases is close to zero. From January to September 2024, hospitalizations in older adults consistently remained higher than the average observed between 2000 and 2023, with the average number of hospitalizations in 2024 (137 ± 28) being 34% higher than the previous years (56 ± 2). In the adult age group, although there was an increase (61 ± 14 in 2024 compared to 56 ± 2 from 200–2023), it is less significant (around 9%).

Similar to cerebrovascular diseases, cardiovascular diseases (Fig. 4c) primarily affect older adults (343 ± 29 hospitalizations/year), followed by adults (232 ± 14 hospitalizations/year). The number of children hospitalized due to cardiovascular diseases was close to zero. Among the three disease groups analyzed, this was the only one that showed a reduction in the number of hospitalizations compared to the period from January to September in 2000–2023. In the older adults, a reduction of around 5% was observed (311 ± 52 in 2024 compared to 327 ± 55 in 2000–2023), and in adults, the reduction was approximately 22% for adults (181 ± 28 in 2024 compared to 231 ± 22 from 2000–2023).

Table 1 shows the IRR estimate for the analyzed age groups based on the meteorological variables and pollutants indicated in the Methods section. Regarding respiratory diseases, children are greatly affected by the T^{Median} (IRR = 1.07–95%CI [1.05–1.09]), while PM_{10}^{Mean} and NO_2^{Mean} also play significant roles (IRR = 1.02–95%CI [1.00–1.04] and 1.01–95%CI [1.00–1.01], respectively). These results indicate that, for example, a 10 ug/m^3 increase in PM_{10}^{Mean} concentration can lead to a 20% increase in children hospitalized for respiratory diseases. Therefore, the combined increase in temperature, PM_{10}, and NO_2 observed during the first week of September explains the approximately 77% increase in children hospitalized for respiratory diseases. In contrast, adults are more affected by $PM_{2.5}^{Median}$ and NO_2^{Mean} (IRR = 1.01–95%CI [1.00–1.01]), while the older adults are primarily impacted by $PM_{2.5}^{Median}$ (IRR ~ 1.01–95%CI[1.00–1.01]).

Only the adult and older adult age groups were analyzed for cerebrovascular diseases, as there were practically no cases recorded for children throughout the historical series (Fig. 4b). In adults the primary factor is T^{Max} with IRR = 1.03–95%CI [1.02–1.04], followed by SO_2^{Mean} (IRR = 1.02–95%CI [1.02–1.02]), RH^{Mean} (IRR = 1.01–95%CI [1.01–1.02]), O_3^{Mean} (IRR = 1.01–95%CI [1.00–1.01]). For instance, a 5 °C increase in T^{Max} can lead to a 15% increase in the number of adults hospitalized for cerebrovascular diseases, for example. Regarding the older adult group, the most significant risk factors are SO_2^{Max} (IRR = 1.02–95%CI [1.01–1.04]) and RH^{Mean} (IRR = 1.01–95%CI [1.01–1.02]).

Similar to cerebrovascular diseases, cardiovascular diseases were analyzed only in the adult and older adult age groups, given the low occurrence of this illness in children, according to DataSUS (Fig. 4c). In adults, the leading risk factor is T^{Max} (IRR = 1.02–95%CI [1.01–1.02]), followed by RH^{Mean} (IRR = 1.02–95%CI [1.01–

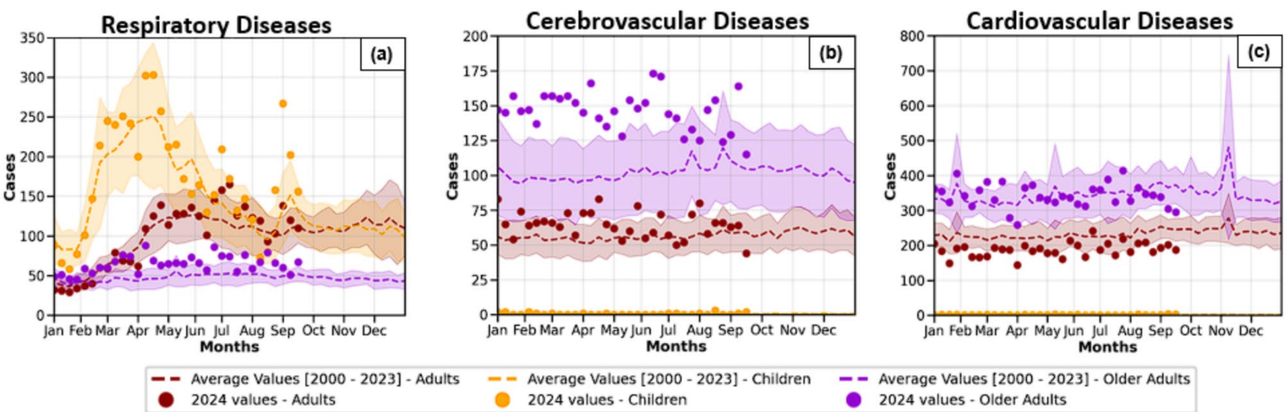

Fig. 4. Cases of respiratory (**a**), cerebrovascular (**b**), and cardiovascular diseases (**c**) observed in adult (red), child (yellow), and older adult (violet) patients in São Paulo Municipality. The dots represent the values observed in 2024, the dotted lines are the average from 2000 to 2023, and the shaded areas represent the standard deviation. Source: DataSUS.

Respiratory disease			Cerebrovascular disease			Cardiovascular disease		
Children								
Variable	IRR	95%CI						
T^{Median}	1.07	1.05–1.09						
PM_{10}^{Mean}	1.02	1.00–1.04						
NO_2^{Mean}	1.01	1.00–1.01						
Adults			Adults			Adults		
Variable	IRR	95%CI	Variable	IRR	95%CI	Variable	IRR	95%CI
$PM_{2.5}^{Median}$	1.01	1.00–1.01	T^{Max}	1.03	1.02–1.04	T^{Max}	1.02	1.01–1.02
NO_2^{Mean}	1.01	1.00–1.01	SO_2^{Mean}	1.02	1.02–1.02	RH^{Mean}	1.02	1.01–1.02
			O_3^{Mean}	1.01	1.00–1.01			
			RH^{Mean}	1.01	1.00–1.01			
Older adults			Older adults			Older adults		
Variable	IRR	95%CI	Variable	IRR	95%CI	Variable	IRR	95%CI
$PM_{2.5}^{Median}$	1.01	1.00–1.01	SO_2^{Max}	1.02	1.01–1.04	T^{Max}	1.02	1.01–1.02
			RH^{Mean}	1.01	1.01–1.02	RH^{Mean}	1.01	1.01–1.02
						SO_2^{Max}	1.01	1.00–1.01

Table 1. Incidence rate ratio (IRR) [95%CI] of respiratory, cardiovascular, and cerebrovascular diseases in São Paulo municipality.

1.02]). These results indicate that a 5 °C increase in T^{Max} may lead to a 10% increase in cardiovascular diseases among adults. For older adults, the primary factor is T^{Max} (IRR = 1.02–95%CI [1.01–1.02]), followed by RH^{Mean} (IRR = 1.01–95%CI [1.01–1.02]) and SO_2^{Max} (IRR = 1.01–95%CI [1.00–1.01]). This indicates that a 10 ug/m^3 increase in the maximum concentration of SO_2 may result in an increase of around 10% in the number of older adults with cardiovascular diseases. Thus, the correlation between SO_2 and cardiovascular diseases justifies why this was the only group to show a reduction compared to the historical average, as SO_2 concentrations in 2024 remained consistently below the historical average.

Discussion

In recent years, the combination of extreme events driven by climate change and unsustainable land use has led to a significant increase in both the frequency and intensity of forest fires, as well as the length of the fire season, in the Southeast, Midwest, and North states of Brazil.

This study showed that the intense drought and high temperatures observed between August (the end of the fire season) and September 2024 likely contributed to an increase in the occurrence of wildfires and an extension of the fire season. These factors led to more biomass-burning episodes during this period, exceeding the historical average by up to 50%. The increase in fires across several Brazilian regions (especially in the Midwest and North, which historically advect smoke plumes to São Paulo Municipality) resulted in higher emissions of pollutants (e.g., NO_2, PM, SO_2). Additionally, due to wintertime and the intense drought in September 2024, less favorable atmospheric conditions for pollutant dispersion led to elevated concentrations of pollutants in São Paulo Municipality.

Between January and September 2024, the number of hospitalizations due to respiratory or cerebrovascular diseases were higher than the average values recorded over the previous 19 years, especially during the fire season. Children and older adults were among the age groups with the most significant variation in respiratory and cerebrovascular diseases, respectively, demonstrating that the most vulnerable groups were the most affected. Additionally, the calculation of the IRR allowed for a detailed analysis of how each pollutant and meteorological variable examined in this study impacts different age groups.

The relationship between $PM_{2.5}$, NO_2, and respiratory diseases, particularly in children, observed in São Paulo Municipality, has also been observed in previous studies conducted in other regions, such as South Africa[51], Hong Kong[52] and Western Amazon[53].

Regarding the cerebrovascular diseases, the association between them and air temperature was also observed by Mascarenhas et al.[54] in a study conducted in 10 Brazilian cities and by Doi et al.[55] in Japan. Doi et al.[55] also identified a positive relationship between relative humidity and cardiovascular diseases, particularly in older adults. Additionally, highlighting the capability of SO_2 and O_3 to cause oxidative stress, Hahad et al.[56] and Miller[57] also identified a relationship between these pollutants and cardiovascular diseases.

The relationship between pollutants, atmospheric variables, and cardiovascular diseases, observed in this study, align with previous studies carried out in São Paulo state[58], China[59], and Iran[60]. Furthermore, the positive relationship between temperature, relative humidity, and cardiovascular diseases has also been observed in other studies in northern and southern China[61] and Taiwan[62].

Therefore, the results presented in this study demonstrate how the increase of fires triggers a cascade effect that leads to higher pollutant concentrations and, consequently, an increase in hospitalizations due to respiratory and cerebrovascular diseases, particularly among the most vulnerable age groups. Moreover, the IRR results provide valuable insights into the potential health implications of a future warmer climate, especially for children and older adults.

Methods

Fire events

The daily number of fire incidents is sourced from the TerraBrasilis platform, developed by the National Institute for Space Research (INPE). The platform's first version was launched in 2019. The platform aims to create a spatial data infrastructure specifically for monitoring data from the Amazon Rainforest Monitoring Program by Satellite (PRODES) and Real-Time Deforestation Detection System (DETER)[63]. All data are available at https://terrabrasilis.dpi.inpe.br/queimadas/bdqueimadas/, which contains records of all fire events detected by satellites and received by INPE since 1998. This study used data from reference satellites covering January 2004 to September 2024.

Pollutant concentration and atmospheric variables

The Environmental Company of the State of São Paulo (CETESB) operates an extensive network of fixed and mobile stations to monitor atmospheric pollutants across the state. The data from this network are made available through CETESB's platform Qualar (https://qualar.cetesb.sp.gov.br/).

Concentration data for $PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2, as well as, values of Air Temperature (T) and Relative Humidity (RH) were extracted from the Qualar platform. All data were collected from all 15 automatic monitoring stations in the São Paulo municipality. Hourly data between January 2004 and September 2024 were selected for this study, so that, from them the median ($\mathrm{Variable}^{\mathrm{Median}}$), maximum ($\mathrm{Variable}^{\mathrm{Max}}$), and mean ($\mathrm{Variable}^{\mathrm{Mean}}$) weekly values were then determined.

Ultra violet aerosol index and aerosol optical depth

The Ultra Violet Aerosol Index is a measurement of the amount of aerosol in the Atmosphere. In this study it was obtained from Visible Infrared Imaging Radiometer Suite (VIIRS) data. VIIRS is part of the Suomi National Polar-orbiting Partnership (NPP)[64], such instrument captures measurements across 22 spectral bands, spanning wavelengths from 0.41 to 12 µm. Among these, 16 are moderate-resolution bands with a nadir spatial resolution of 750 m, while 5 are imaging bands with a higher nadir spatial resolution of 375 m. Additionally, VIIRS features a unique day/night band in the reflective solar spectrum (0.5–0.9 µm), which operates at three different gain stages. This configuration enables an extensive dynamic range, allowing data collection during daytime and nighttime orbits[65].

Using data from the Aerosol Robotic Network (AERONET), the Ångström matrix was estimated using the methodology described in Cappa et al.[66]. This matrix provides information about the type of aerosols and their absorption capacity, measured by the differential Single Scattering Albedo (dSSA). In addition, these same data were used to plot the daily Aerosol Optical Depth (AOD) [440 nm] time series (Fig. 4f) from January 2004 to September 2024.

Diseases

All disease data used in this work were collected from the DataSUS website (https://datasus.saude.gov.br/), a Brazilian Ministry of Health repository to São Paulo Municipality. The data were categorized into three age groups: children (0–14 years), adults (15–59 years), and older adults (60 years or older). The three groups of diseases analyzed comprise the following ICD codes: respiratory (J00, J01, J02, J03, J04, J05, J06, J11, J18, J20, J21, J22, 23, J30, J32, J40, J44, J45, J46, J47), cerebrovascular (I62, I63, I64, G45), and cardiovascular (I10, I11, I15, I20, I21, I24, I26, I45, I47, I48, I49, I50). The data covered the period from January 2000 to September 2024, and for analysis purposes, they were grouped into epidemiological weeks.

Incidence rate ratio (IRR)

The incidence rate ratio (IRR) was estimated using a univariate negative binomial regression. The outcome variable was the number of weekly hospitalizations to each age group (children, adults, and older adults), while the independent variables included the Mean, Median, and Maximum values of Air Temperature (T), Relative Humidity (RH), and concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3. The initial negative binomial regression model included all variables. Variables with a *P-value* greater than 0.01 were removed using manual backward stepwise elimination. The final model was created based on the most relevant variables. This approach enables us to assess how different variables affect each age group.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request, and at CAIPORA Project website (https://portalcaipora.org/dados/downloads).

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Author contributions

G.A.M, A.C. and I.S.A. analyzed the results and developed all algorithms. G.A.M., S.C., I.S.A., A.C., and J.L.G.R. wrote the main document. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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