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Using mobile air quality station data to identify critical areas in the city of Rio de Janeiro regarding pollutant concentrations

Uso de uma estação móvel de monitoramento da qualidade do ar para identificar as áreas críticas quanto à qualidade do ar na cidade do Rio de Janeiro

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ABSTRACT

Recent studies have shown that tropospheric ozone, fine particulate matter and nitrogen dioxide are the urban air pollutants of major concern regarding human health effects. Monitoring air quality is a challenge in several cities, such as Rio de Janeiro, where the number of fixed-site air quality monitoring stations and their spatial distribution are insufficient to assess the extent of atmospheric pollutants. However, despite this lack of resources, the data obtained by mobile stations are a valuable means of determining which areas are experiencing critical air quality conditions, and provide key information for an air quality management program. The main purpose of this study was to conduct a critical analysis of data obtained by the Municipal Department of Environment and Climate (SMAC) mobile station in the period 2010–2018. Concentrations determined for particulate matter with a diameter ≤2.5 µm ($PM_{2.5}$), O_3, NO_2, SO_2 and CO showed that $PM_{2.5}$ and O_3 are the pollutants of major concern, and that the north of the city has higher air quality indices for these compounds. In addition, the south-west district had relatively high ozone levels, probably owing to low concentrations of NO_2 in a volatile organic compound (VOC)-limited ozone formation regime. These factors should be considered by the municipal government in future discussions of control strategies for managing the city's air quality. This study also shows the value of mobile stations in making a preliminary survey of pollutant concentrations, mainly in countries with limited financial investment in air quality management.

Keywords: mobile monitoring stations; air quality management; ozone; fine particulate matter; Rio de Janeiro.

RESUMO

Estudos recentes têm mostrado que o ozônio troposférico, o material particulado fino e o dióxido de nitrogênio são os poluentes urbanos de maior importância quanto aos efeitos sobre a saúde humana. O monitoramento da qualidade do ar é um desafio, especialmente em cidades como Rio de Janeiro, onde o número e a distribuição das estações de monitoramento fixas é insuficiente para avaliar a distribuição dos poluentes atmosféricos. Contudo, apesar da limitação dos recursos, dados obtidos por estações de monitoramento móveis são de grande utilidade para determinar quais áreas experimentam condições críticas de qualidade do ar e fornecem informações úteis para os programas de gerenciamento da qualidade do ar. O principal objetivo deste estudo foi realizar uma análise crítica dos dados obtidos pela estação móvel da Secretaria Municipal de Ambiente e Clima (SMAC), no período 2010–2018. Os resultados obtidos para material particulado com diâmetro ≤2,5 µm ($MP_{2,5}$), O_3, NO_2, SO_2 e CO mostram que $MP_{2,5}$ e O_3 são os poluentes que geram maior preocupação, e que a zona norte da cidade tem os piores índices de qualidade do ar para esses compostos. Além disso, a área sudoeste apresenta níveis relativamente altos de ozônio, provavelmente em razão das baixas concentrações de NO_2 em um cenário onde a formação de ozônio é controlada pelos compostos orgânicos voláteis (COV). Esses fatores deveriam ser considerados pelo governo municipal em futuras discussões de estratégias para o gerenciamento da qualidade do ar da cidade. Este trabalho mostra, também, a contribuição das estações móveis de qualidade do ar para realizar um estudo preliminar das concentrações de poluentes, especialmente em países com recursos financeiros limitados para o gerenciamento da qualidade do ar.

Palavras-chave: estações móveis de monitoramento; gerenciamento da qualidade do ar; ozônio; material particulado fino; Rio de Janeiro.

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Introduction

Since 1987, the World Health Organization (WHO) has published global Air Quality Guidelines (AQGs), which have served as targets for national, regional and municipal governments to work towards improving air quality and human health. In September 2021, WHO released a new report with an update of the air quality guidelines (WHO, 2021). In the last decade, there has been a good deal of evidence showing that air pollution affects human health in lower concentrations than previously thought, and one of the key objectives of the report was to stress the need to redouble efforts to protect communities from the health risk of air pollution (WHO, 2015, 2021). WHO also recognizes that there is a link between air pollution, global ecosystems and the earth's climate zones. Thus, the reduction of air pollution has a beneficial effect on health, and could also lead to both short and long-term climate change mitigation (WHO, 2022a).

The main contribution of the 2021 report is the revised guideline values for particulate matter reduction owing to the health risks caused by particulate matter with a diameter equal to or less than 10 and 2.5 µm (PM_{10} and $PM_{2.5}$, respectively) (WHO, 2005, 2021). In the case of $PM_{10,}$ the values were reduced from 20 and 50 µg m^{-3} to 15 and 45 µg m^{-3}, for the annual mean and the 24-hour mean, respectively. In the case of $PM_{2.5,}$ the maximum values were reduced from 10 and 25 µg m^{-3} to 5 and 15 µg m^{-3}, for the annual mean and the 24-hour mean, respectively. With regard to NO_2, the 2005 WHO report considered a 1-hour mean of 200 µg m^{-3}. In the 2021 report, 24-hour means were proposed, together with an initial interim value of 120 µg m^{-3} (which was regarded as roughly comparable to the existing 1-hour mean) and a final value of 25 µg m^{-3} (WHO, 2005, 2021). Interim targets for the reduction of pollutants were also published (WHO, 2021). The new values, as well as the 2005 AQGs, are shown in Table 1.

As discussed in the report (WHO, 2021), in many countries of the world monitoring coverage (using fixed monitoring stations) is inadequate to characterize the spatial variations. Since 2010, alternative methods have been used to address these gaps, such as satellite data retrievals, chemical transport models and land-use regression models. Other methods, such as mobile automated monitoring stations and low-cost equipment, have been suggested as an alternative to obtain preliminary survey data (Albarracin et al., 2023; da Silva, 2023).

Table 1 – World Health Organization PM_{10}, $PM_{2.5}$ and NO_2 Air Quality Guidelines and interim targets published in 2021 to guide the pollutant reduction. Air Quality Guidelines values stablished in 2005 are also shown for comparison.

Pollutant	Averaging time	AQG level*	Interim target**				AQG level
			1	2	3	4	
$PM_{2.5}$ (µg m^{-3})	Annual	10	35	25	15	10	5
	24-hour[a]	25	75	50	37.5	25	15
PM_{10} (µg m^{-3})	Annual	20	70	50	30	20	15
	24-hour[a]	50	150	100	75	50	45
NO_2 (µg m^{-3})	1-hour	200					
	24-hour[a]		120	50			25

*WHO (2021); **WHO (2005).

Since 2011, WHO has compiled and published ground level measurements of pollutant concentrations, in 117 countries and 6,743 urban centers (cities and towns). Data show that the coverage of ground measurements is not uniform around the globe (WHO, 2022b). Most of the data were obtained for high- and middle-income countries (China, India, and countries in Europe and North America). Moreover, according to the database, low- and middle-income countries in South America and the Caribbean have a low coverage. In particular, in the case of Brazil, with a territory of 8,510,417.771 km², 203 million inhabitants and 5,570 urban centers (IBGE, 2023), only 16 cities were included in the report (Dantas et al., 2021). Recently, a comprehensive analysis was published by Sicard et al. (2023) using data for 13,260 urban areas obtained between 2000 and 2019. In Brazil, the available data showed that O_3 (daily maximum 8 h values) increased in the period 2010–2019 in 99% of urban areas (cities with more than 50,000 inhabitants). Clearly, a more complete coverage, more investments and alternative approaches in air quality managements are needed (Dantas et al., 2021; Sicard et al., 2021, 2023).

With regard to Brazilian legislation, the National Environmental Council (CONAMA) established, in 2018, the National Air Quality Standards (NAQS), through the CONAMA Resolution nº 491, which is based on the 2005 WHO AQGs (WHO, 2005; CONAMA, 2018). The Resolution lays down three interim target values (IT), as well as a final value. The first IT values (IT-1) were adopted immediately but there is no predetermined data to suggest when the following interim targets and the final NAQS should be adopted (Siciliano et al., 2019). The Brazilian NAQS and the WHO AQGs are reported in the literature (and are available as Supplementary Material).

According to Brazilian legislation, air quality monitoring and management should be undertaken by the Ministry of the Environment and the environmental agencies of each state (and the Federal District) (CONAMA, 2018). The State Environmental Institute (INEA) publishes a daily report with the air quality index (AQI) for 16 monitoring stations located in the Metropolitan Region of Rio de Janeiro (MRRJ), which has a total population of approximately 13 million inhabitants, and 22 municipalities, including the city of Rio de Janeiro, the state capital (INEA, 2023). The daily reports have no information about individual pollutant concentrations, not allowing the observation of which pollutants are being monitored, and indicating only the most critical for each day. In the city of Rio the Janeiro, with an area of 1,200 km² and a population of approximately 6,2 million people, eight automated fixed-site air quality monitoring stations are being operated by the Municipal Department of the Environment (SMAC) since 2012 (SMAC, 2023a). Nevertheless, according to the available data, in the city of Rio de Janeiro all criteria pollutants are determined in only one station, located in Irajá (SMAC, 2023b). The literature has recognized that the coverage and financial investment in air quality management in the city are insufficient (Dantas et al., 2021; IEMA, 2022). In view of the lack of resources, alternative methods could be used to meet the rising needs for a flexible and cost-effective way to conduct air quality measurements.

Mobile platforms, including motorized vehicles, bicycles, light rails and backpacks, may complement existent fixed networks or obtain data where ground-based equipment is not available (Lee et al., 2020; Padilla et al., 2022). This approach has been used in different cities, mainly to characterize traffic-related air pollution. For example, Blanco et al. (2022) measured $PM_{2.5}$, NO_2 and CO_2 at 309 roadside sites (approximately 29 two-minute measurements at each site) over a 1-year period in the Greater Seattle Area (U.S.A.). Alternatively, mobile air monitoring stations could be temporary installed in a location (for some weeks or months) and, then, moved to another location. In general, this approach is useful when carrying out specific measurement campaigns in different locations, and allow more opportunity to assess air quality in a city using temporary sites to develop a meaningful picture (Kelly et al., 2023).

A mobile automated air quality monitoring station was successively installed by the SMAC in several locations of the city of Rio de Janeiro, in the period 2010–2018, which collected data containing the concentrations of $PM_{2.5}$, O_3, SO_2, CO and NO_2 (SMAC, 2023a, 2023c). These data succeeded in enabling an extensive survey of the Rio de Janeiro air quality, but, in spite of their importance and of being available through DataRio platform (Data Rio, 2022), so far, they have not been analyzed and published as a literature study. The main goal of this study is to analyze the data obtained by the SMAC mobile station in the city of Rio de Janeiro and identify the areas with critical air quality conditions considering the WHO AQG. It is hoped that the conclusions of this study will be used by the municipal government in future discussions about managing the air quality of the city.

Materials and Methods

the city and the Metropolitan Region of Rio de Janeiro

The MRRJ has been described in a previous study (Silva et al., 2017). More than 35% of the MRRJ is covered by the Atlantic rain forest (both primary and secondary forests), including the Pedra Branca and Gericinó-Mendanha parks, which form a natural boundary that separates the west district from the rest of the city. The Tijuca Massif (1,022 m high) and the Tijuca Forest divide the north and south sectors of Rio de Janeiro. This forest was declared a national park in 1961, and is considered to be the largest secondary urban forest in the Americas and one of the two largest secondary urban forests in the world. Pedra Branca State Park, in the west of Rio de Janeiro, is one of the largest primary urban forests in the world and Pedra Branca Massif (1,024 m) is the highest point in the city. The role of urban forests in improving air quality has been recently acknowledged for Rio de Janeiro (Arbilla et al., 2023) and São Paulo (Brito and Rizzo, 2022). The Atlantic Ocean and Guanabara Bay also play an important role in air mass circulation (Dantas et al., 2021).

The main sources of anthropogenic emissions have already been discussed in detail (Dantas et al., 2021; Arbilla et al., 2022). Briefly, in the north there are several chemical and pharmaceutical industries (particularly in the towns of Duque de Caxias, Belford Roxo and São João de Meriti). Duque de Caxias also has a thermo-electric plant and several petrochemical companies, including Duque de Caxias Refinery, which accounts for the largest amount of natural gas processing in the country and approximately 80% of lubricant production (Petrobras, 2022). The Port of Rio de Janeiro, with offshore support bases in Guanabara Bay, is located in the north of the city (CDJ, 2022a). The Port of Niterói, on the eastern coast of Guanabara Bay, has offshore support bases and construction site platforms, as well as naval machinery (Porto de Niterói, 2015). In the western district of the MRRJ, there are several metallurgical companies (aluminum and steel), including the largest steel mill in South America, together with food industries, and there are also factories and plants related to agriculture, livestock and mining (Ternium, 2022). The second largest Brazilian port (the Port of Itaguaí) is located alongside Sepetiba Bay (in the western district) (CDJ, 2022b).

The main avenues and highways of the city have been described in a previous study (Arbilla et al., 2022). According to the vehicular emission inventory published by INEA, the city of Rio de Janeiro is responsible for approximately 50% of the primary particulate matter caused by vehicular emissions, particularly in the north and west (23 and 21%, respectively). Particulate matter (98%) and nitrogen oxides (65%) are emitted by diesel vehicles (trucks and buses) while non-methane hydrocarbons are mainly emitted by light vehicles (78%) (INEA, 2013).

The city of Rio de Janeiro experienced an important reconfiguration of the urban landscape as a consequence of many mega-events, initiating with the 2007 Pan American Games and, then, the 2011 Military Games, the 2010 World Urban Forum, the 2013 World Youth Day and, mainly, the 2014 FIFA World Cup and the 2016 Olympic Games (Sánchez and Broudehoux, 2013). The social, economic and environmental impact of the World Cup and the Olympic Games have been discussed by several authors (Gaffney, 2016; Ventura et al., 2019, 2021; Yamawaki et al., 2020). The main modifications in transport and urban landscape are shown in Table 2. The number of vehicles in the city, according to the Brazilian Institute of Geography and Statistics (IBGE), is also indicated.

Studied locations

The SMAC mobile monitoring station was installed in several locations of the city of Rio de Janeiro in the period 2010–2018. Decisions about the sampling sites and the dates were made by the environmental agency in accordance with their monitoring programs and took account of security conditions and the availability of the necessary equipment. Since only one mobile monitoring station was available, no simultaneous records for different locations were obtained and it was not possible to compare them. This is a limitation inherent to the restricted resources of the monitoring campaign. A description of the sampling sites, pollution sources and dates are shown in Table 3, and more detailed information can be obtained as Supplementary Material. A map indicating the sampling points is included in the Results and Discussion section.

Table 2 – Main modifications in transport and urban landscape in the city of Rio de Janeiro (2011–2018).

Year	Events
2011	Number of vehicles: 2,190,325
2009–2016	Porto Maravilha (Rio's vast port revitalization project)
2010–2016	Expansion of subway network (line 4) between Ipanema and Barra da Tijuca (the construction of the Gávea station was not concluded)
2010–2013	Maracanã Stadium makeover for the World Cup 2014
2012–2016	Implementation of VLT (28-km light rail line) in Centro and Port area
2012–2014	Construction of Providência Cable Car connecting Américo Brum Square (at the top of the hill) to Central do Brasil Station and Gamboa (721 m)
2012–2016	Construction of the three Bus Rapid Transit (BRT) corridors
2012–2016	Construction of the Olympic Park in Barra (west area of Rio de Janeiro. The park includes the Complexo Esportivo Cidade dos Esportes, built for the 2007 Pan American Games, and housed nine sports facilities during the Olympics; eight of them are permanent, and only one was meant to be temporary.
2014	2014 FIFA World Cup
2015–2016	Expressway doubling São Conrado–Barra (Elevado do Joá) with an increase of 30% in the vehicular flux
2016	Part of Rio Branco Avenue was closed, between Nilo Peçanha Avenue and Santa Luzia Street, and a pedestrian walk way (600 m) was constructed.
2016	2016 Olympic Games
2018	Number of vehicles: 2,827,516

Experimental data

Data were obtained by the SMAC through the use of reference or equivalent methods and instruments (a detailed description is available as Supplementary Material) in accordance with Brazilian legislation and the recommendations of the Technical Guide for Monitoring and Air Quality Evaluation published by the Ministry of the Environment (CONAMA, 2018; MMA, 2019). The methods and data validation procedure followed the recommendations of the US Environmental Protection Agency (EPA, 2016, 2021). On the basis of the Brazilian Technical Guide (MMA, 2019), data were considered for the calculations when the following conditions were met: 3/4 and 2/3 of the valid data for a 1-hour and 24-hour average, respectively.

Calculations and figures were obtained by means of the R language and the Openair package (Openair, 2022; R, 2022). The periods averages were calculated in accordance with Brazilian legislation (CONAMA Resolution nº 491): a 24-hour average for $PM_{2.5}$ and SO_2, maximum 1-hour average for NO_2 and maximum 8-hour average for CO and O_3 (CONAMA, 2018). The values for each monitoring location were arranged as boxplots, which provide a better description of data distribution. The AQI were calculated as recommended by Brazilian legislation and the following colors were used in the figures: green (good), yellow (moderate), orange (unhealthy), red (very unhealthy). The AQI are discussed in the literature (MMA, 2019; Siciliano et al., 2019; CETESB, 2022).

Results and Discussion

For brevity, the results for SO_2 and CO are available as Supplementary Material. All CO maximum 8-hour average values were <9 ppm and the median values for all stations were <1 ppm, that is, a "good" AQI with regard to this pollutant (MMA, 2019; CETESB, 2022). The highest values were obtained in Centro and can be attributed to vehicular emissions (cars and motorcycles). Avenue Rio Branco, in close proximity to the monitoring station (which has been closed to traffic since 2016) was a significant source of emissions in 2010 (see Table 2). This was an expected result since, in general, CO levels are relatively low in the city of Rio de Janeiro (SMAC, 2012, 2022b).

All the median values for SO_2 were <20 μg m^{-3}, that is, a "good" AQI for this pollutant (MMA, 2019; CETESB, 2022). Many values >20 μg m^{-3} were obtained in Caju and the area of the Port (Gamboa and Porto Maravilha) and could have been caused by local emissions arising from port activities, trucks, machines and ship fuel (bunker oil).

Maximum 1-hour means for NO_2 are shown in Figure 1. These values were not obtained in all the locations because of mechanical failures (in 2014 the measurement procedure was interrupted because the instrument employed had a technical failure and could not be replaced). All the values were <200 μg m^{-3}, that is, a "good" AQI with regard to this pollutant as specified in Brazilian legislation (MMA, 2019; CETESB, 2022). Higher values were obtained in Centro, Maracanã, Vicente de Carvalho and Del Castilho and can be attributed to vehicular emissions (mainly from buses) (INEA, 2013). Several studies carried out during the partial lockdown imposed in Rio de Janeiro, in March-April 2020, to prevent the spread of COVID-19, as well as data obtained during a 10-day national strike of the road freight hauliers (in 2018), showed a sharp reduction of NO_2 levels during these periods, which confirms that heavy traffic is the main contributory factor in NO_2 levels within the urban area (Dantas et al., 2021; Ventura et al., 2021).

Table 3. Sampling sites and dates, main characteristics and pollutant sources of studied locations.

Sampling site and date	Main characteristics	Main pollutant sources
Centro -22.90491, -43.17749 05/11/2010 – 07/21/2010	Mixed urban or built-up land, commercial and residential (predominantly commercial/services).	-Vehicular emissions (cars, motorcycles and buses); -natural sources (in particular, marine aerosol); -Santos Dumont Airport and the Port of Rio de Janeiro (approximately 3 km from the mobile monitoring station).
Vicente de Carvalho (-22.85382, -43.31063) 07/22/2010 – 12/17/2010	Mixed urban or built-up land, commercial and residential (predominantly residential).	-Local sources: vehicular emissions (cars, motorcycles and buses); -transport from the northern industrial region (pharmaceutical, chemical and petrochemical companies).
Campo Grande (-22.88667, -43.55659) 12/27/2010 – 02/15/2011	Mixed urban or built-up land, heterogeneous mixture (commercial, residential, industrial and agriculture).	-Local sources: vehicular emissions (cars, buses, trucks and motorcycles), natural sources (dust, vegetation), agriculture, livestock, mining activities and industrial emissions (food and pharmaceuticals); -transport from other companies in the western district, especially Santa Cruz (steel and metallurgical industry) and the Port of Itaguaí.
Bangu (I) -22.88865, -43.46969 02/16/2011 – 04/12/2011 and Bangu (II) -22.87120, -43.459389 12/01/2016 – 09/08/2017	Mixed urban or built-up land, commercial and residential (predominantly residential).	-Local sources: vehicular emissions (cars, buses, trucks and motorcycles) and natural sources (mainly dust and vegetation); -transport of vehicular emissions from the west and the east (mainly from the town center) and industrial emissions from the west (Campo Grande and Santa Cruz).
Pedra de Guaratiba -23.00395, -43.62954) 04/13/2011 – 06/15/2011	Mixed urban or built up land, residential, fishing industry, recreational land (predominantly residential).	-Natural emissions (mainly dust and marine aerosol); -Emissions from the Port of Itaguaí in Sepetiba Bay, which is the second largest Brazilian port (steel, iron ore, containers and solid bulk cargoes).
Gávea (Avenue Padre Leonel França, S/N – PUC University) 06/23/2011 – 10/31/2011	Mixed urban or built up land, commercial/services and residential (predominantly residential).	Local vehicular emissions (cars, buses and motorcycles). Natural emissions (mainly dust and marine aerosol).
Maracanã -22.91072, -43.23610 11/21/2011 – 03/28/2012	Mixed urban or built-up land, commercial/services and residential (predominantly residential). Sports and cultural centers including the Maracanã Stadium and the surrounding complex.	Local vehicular emissions (cars, buses, trucks and motorcycles).
Del Castilho (Ademar Bebiano Street, 339 – Clinic Rodolpho Rocco) 06/20/2012 – 09/27/2012	Mixed urban or built-up land, commercial/services and residential (predominantly residential).	-Local vehicular emissions (cars, buses, trucks and motorcycles); -pollutants carried from the north and north-east (industrial and vehicular emissions).
Port of Rio (I); (II) -22.89483, -43.17939 09/28/2012 – 02/18/2013 09/23/2013 – 01/13/2014	Mixed urban or built-up land (predominantly commercial/services and port facilities).	-Local vehicular emissions (cars, buses and trucks); -local emissions caused by the harbor activities, trucks, machines and ship fuel (bunker oil); -natural emissions, mainly marine aerosol.
Caju (I) -22.87464, -43.222209 02/21/2013–08/28/2013; Caju (II) -22.87535, -43.211587 09/18/2014–04/17/2015; Caju (III) -22.87998, -43.22695 08/21/2015 – 01/13/2016	Mixed urban or built-up land (predominantly commercial/services, industrial and Port facilities).	-Local vehicular emissions (cars, buses and trucks). Local emissions caused by port and industrial activities, as well as the sewage plant; -natural emissions, mainly marine aerosol.
Madureira Park -22.86960, -43.34034 01/14/2014 – 08/12/2014	Mixed urban or built-up land, heterogeneous mixture (commercial/services, residential, industrial and recreational area).	-Local vehicular emissions (cars, buses, trucks and motorcycles); -pollutants carried from the north and north-east (industrial and vehicular emissions).
Porto Maravilha -22.89454, -43.18864 02/17/2016 – 05/20/2016	Mixed urban or built-up land, heterogeneous mixture (commercial/services, administrative, cultural and recreational area, port facilities).	-Local vehicular emissions (cars, buses and motorcycles); -natural emissions, mainly marine aerosol.
Cantagalo -22.97559, -43.19403 08/02/2016 – 11/26/2016	Mixed urban or built-up land, commercial/services and residential (predominantly residential).	-Local vehicular emissions (cars, buses and motorcycles); -natural emissions, mainly marine aerosol.
Recreio dos Bandeirantes -23.01991, -43.48143 10/11/2017 – 03/12/2018	Mixed urban or built-up land, commercial/services and residential (predominantly residential), alongside the Atlantic Ocean and near Pedra Branca Massif.	-Local vehicular emissions (cars, buses and motorcycles); -natural emissions, mainly marine aerosol.

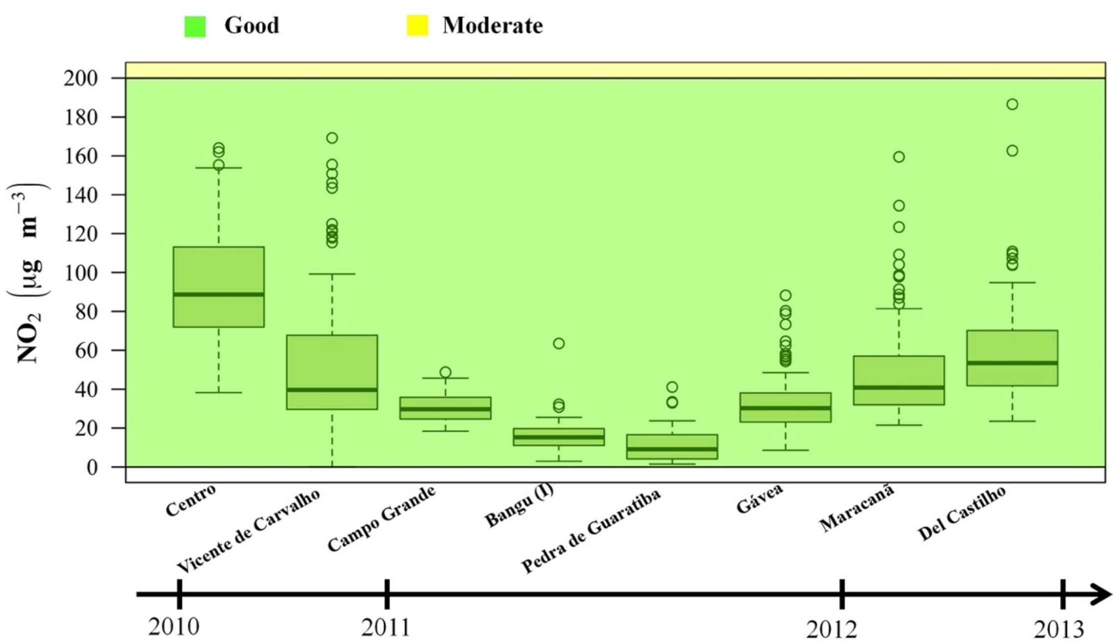

Figure 1 – Maximum 1-hour mean for NO_2. The years (at the bottom of the figure) indicate the approximate monitoring time period. All the values were within a "good" AQI for this pollutant in accordance with Brazilian legislation.
Source: MMA (2019).

NO_2 is a serious atmospheric pollutant because of its health risks, and also owing to the critical role it plays in tropospheric chemistry (both in the formation and consumption of ozone), the radical generation and fate control (including hydroxyl radicals) and the formation of secondary particulate matter (mainly $PM_{2.5}$) (Finlayson-Pitts and Pitts Jr., 2000; Orellano et al., 2020; WHO, 2021). On the basis of new evidence concerning long-term exposure and all non-accidental mortality data, WHO recommended a maximum annual mean of 10 µg m^{-3} (WHO, 2021). In the case of short-term exposure, the maximum 24-hour mean recommended by WHO is 25 µg m^{-3} (WHO, 2021). 24-hour averages for the studied locations were also calculated and are available as Supplementary Material (WHO, 2021).

Results showed that, in Centro, 100% of NO_2 24-hour means are >25 µg m^{-3}. Approximately 50% of data obtained in Vicente de Carvalho and Maracanã and 75% of the averages in Del Castilho are also >25 µg m^{-3}. The extent of long-term exposure was not calculated since the monitoring station had been operating for less than 12 months in all the studied sites, but the averages for the studied period were calculated (data available as Supplementary Material). The calculated values were >10 µg m^{-3}, which is the annual limit according to WHO (WHO, 2021), except for Pedra de Guaratiba. In Centro, the mean value for 72 days was 63.6 µg m^{-3} and in Vicente de Carvalho (149 days), Del Castilho (100 days) and in Maracanã (129 days), the mean values were >30 µg m^{-3}, which suggests that the annual mean would probably be >10 µg m^{-3} and that long-term exposure represents a risk to human health.

The maximum 8-hour averages for O_3 are shown in Figure 2. All the median values are <100 µg m^{-3}, as well as the values in the Q1, Q2 and Q3 quartiles, which suggests that at least 75% of the values correspond to "good" air quality for this pollutant. The only exception is Bangu I (by a Kindergarten in Mongólia Street), a location which experiences frequent high ozone concentrations, according to the fixed automatic monitoring station located in this district (Geraldino et al., 2020; SMAC, 2023a, 2023b).

As discussed by Siciliano et al. (2019), the previous Brazilian NAQS (CONAMA Resolution 03/1990) established a 1-hour mean (a maximum of 160 µg m^{-3}) and the limits for "good" and "moderate" AQI were set as 80 and 160 µg m^{-3} (CONAMA, 1990). The increase of the averaging period (8-hours) and the new values to determine the AQI led to lower indices. In the case of the 1-hour means, the number of days with a "good" AQI is 72.0%, compared with 94.8%, which is calculated by means of data from Figure 2 (an 8-hour average) and the present AQI limits.

Processes leading to ozone formation and consumption depend, in a non-linear way, on volatile organic compounds (VOC) and NO_x (NO_x=NO_2+NO) concentrations, as well as on VOC speciation and reactivity. The complexity of the ozone chemistry has been fully described (Finlayson-Pitts and Pitts Jr., 2000), and several studies were carried out in the period when restrictive measures were imposed during the COVID-19 lockdown, which confirmed the strong dependence on VOC/NO_x ratios (Cazorla et al., 2020; Kroll et al., 2020; Siciliano et al., 2020). Unfortunately, VOC concentrations were not determined by the mobile monitoring station and the NO_2 data are limited (see Figure 1).

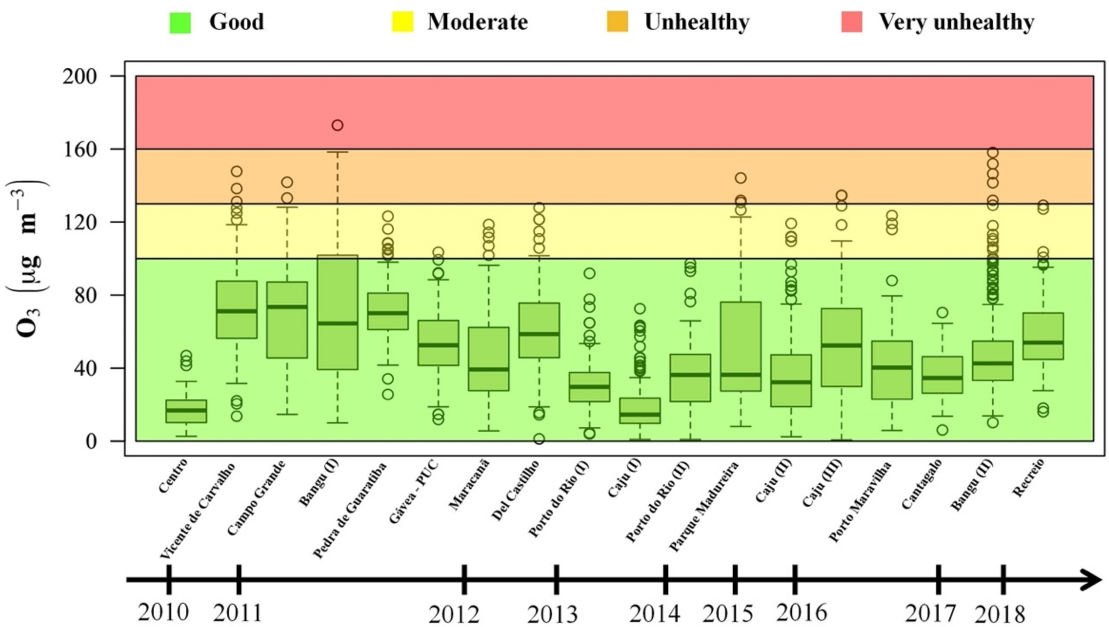

Figure 2 – Maximum 8-hour means for O_3. The air quality index was indicated by following the guidelines of Brazilian legislation. The years (at the bottom of the chart) indicate the approximate monitoring time period.
Source: CONAMA (2018) and MMA (2019).

Nevertheless, Figures 1 and 2 suggest that the lower ozone levels detected in the Centro and Caju districts were due to higher NO_2 levels, in a VOC-limited regime (Sillman, 1999; Silva et al., 2018; Kroll et al., 2020). Data obtained by the fixed air quality monitoring station located in Centro (since 2010) showed that O_3 levels increased after the urban interventions in 2016, when a part of Rio Branco Avenue (next to the monitoring station) was closed to traffic. Unfortunately, the fixed-site station does not measure NO_2 and hydrocarbons levels, and is thus unable to confirm this hypothesis (SMAC, 2023b). Bangu and other districts in the north of the city (such as Madureira and Del Castilho) showed higher ozone levels and are characterized by a mixture of emission sources (both vehicular and industrial) and higher VOC/NO_x ratios (Dantas et al., 2020).

Ozone concentrations are also related to meteorological parameters (mainly temperature and solar radiation) as well as transport of air pollutants (Silva et al., 2021). In general, ozone levels increase in summer and spring due to the combination of higher temperature and solar radiation and the decrease in nebulosity, however high ozone episodes have been registered in Rio de Janeiro during winter, due to low mix layer heights and the increase in primary pollutants concentrations (SMAC, 2023b). Meteorological data and estimated vehicular emissions are not available for a further analysis.

In Figure 3, 24-hour means for $PM_{2.5}$ are shown. Clearly, in light of Brazilian legislation and the studied locations, $PM_{2.5}$ is the pollutant that causes major concern in Rio de Janeiro (CONAMA, 2018). Approximately 19.6% of the values are >25 μg m^{-3}. Furthermore, when the maximum 15 μg m^{-3} value (recommended by WHO) is considered, 51.5% of the data are higher, which suggests that short-term exposure to $PM_{2.5}$ is high and could lead to cause-specific mortality (WHO, 2021).

These results are in the same range as the values found in other studies carried out in 2010–2018. Godoy et al. (2018) measured the $PM_{2.5}$ levels and chemical composition during the period from June 2012 to June 2013 at four sampling points in the MRRJ (districts of Barra da Tijuca, Taquara and Tijuca, in the city of Rio de Janeiro, and Duque de Caxias). Annual mean values were within the 8–12 μg m^{-3}range. As reported by the authors, the annual and 24-hour mean values were within the limits of the 2005 WHO AQGs, but when the new WHO recommendations are considered, the annual mean values were higher and there were frequent violations of the 24-hour AQG (Godoy et al., 2018). A similar conclusion can be reached from the data obtained in 2016, which included the Olympic Games event (Ventura et al., 2019). Annual and 24-hour concentrations were within the limits of Brazilian legislation and the 2005 WHO AQGs, but the values were high when compared with the 2021 WHO recommended limits (CONAMA, 1990, 2018; WHO, 2005, 2021).

Long-term exposure (i.e. the annual mean values) could not be calculated since the monitoring station had only been installed for less than twelve months in all the studied sites. The WHO recommendation is an annual $PM_{2.5}$ maximum level of 5 μg m^{-3} (WHO, 2021). However, to provide a rough comparison, the averages for the studied periods in each location were calculated. The total numbers of days was between 51 (Campo Grande) and 284 (Bangu I), and the mean values in the range of 8.5–29.7 μg m^{-3} suggest that the annual mean values may be high in comparison with WHO AQG, and also higher than the WHO Interim target 4 (10 μg m^{-3}) except for Cantagalo (10 μg m^{-3}), in the south district.

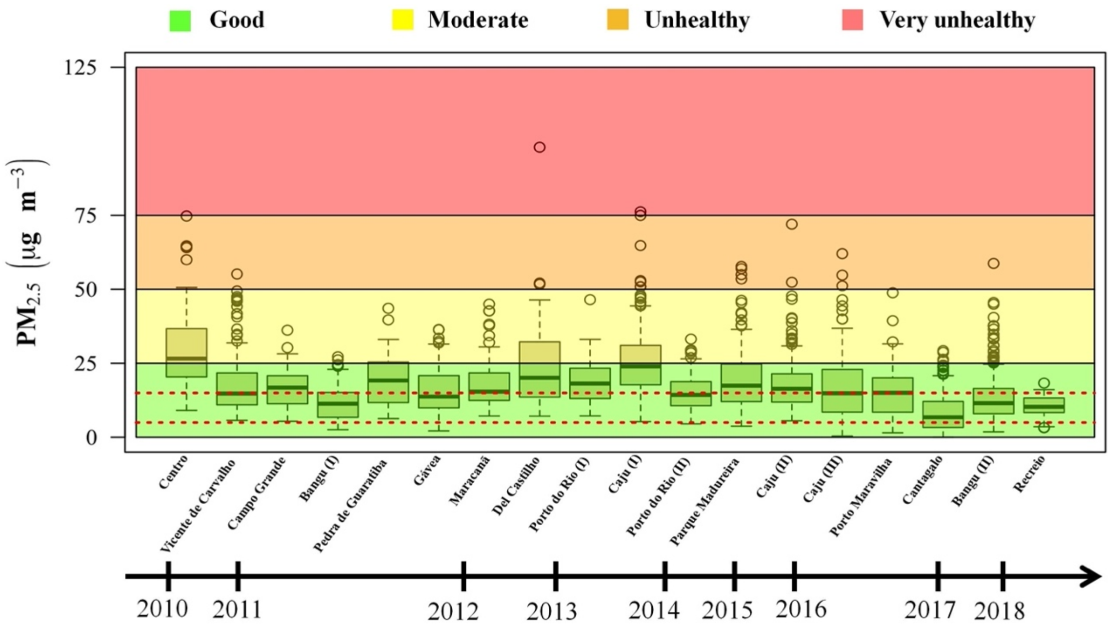

Figure 3 – 24-hour means for particulate matter with a diameter ≤2.5 µm ($PM_{2.5}$.) The red lines indicate the World Health Organization recommendations for annual (5 µg m^{-3}) and 24-hour (15 µg m^{-3}) means. The years (at the bottom of the chart) indicate the approximate monitoring time period.
Source: WHO (2021).

Figure 4 shows the pollutants of major concern and the most critical areas. The southern district had lower pollutant levels because of the influence of air masses from the Atlantic Ocean which allow air circulation. The western and northern region, where the massifs form natural barriers to air circulation, showed higher levels of both O_3 and $PM_{2.5}$.

The northern and western region of the city (Campo Grande, Bangu, Del Castilho and Vicente de Carvalho) are characterized by higher O_3 levels. This was an expected result, since the fixed monitoring stations located in Irajá (which was not studied in this work), Bangu and Campo Grande often show high AQI values for this pollutant (Dantas et al., 2020; Geraldino et al., 2020; SMAC, 2012, 2023a, 2023b). As previously discussed (Dantas et al. 2021), in this region, the wind circulation is influenced by Guanabara Bay, and it is affected by the north-east air masses originating from the industrial (largely chemical, pharmaceutical and petrochemical) complex (situated in Duque de Caxias, Belford Roxo and São João de Meriti). It is also influenced by the south and south-east winds which carry the pollutants emitted by traffic in the town center and the main highways and avenues (Brazil Avenue, Linha Vermelha and Linha Amarela). VOC/NO_x ratios are expected to be higher and the VOC mixture more reactive when winds are from the industrial area, favoring ozone formation.

Ozone concentrations were also high in Pedra de Guaratiba (in the south-west). This is a residential district on the coast of Sepetiba Bay (Atlantic Ocean), with a low traffic flow of buses and trucks, winds from the south and air circulation provided by sea breezes (Arbilla et al., 2022). As shown in Figure 1, NO_2 levels were low and, although there is no data regarding VOC, high VOC/NO_x ratios are expected (both because of the low NO_2 levels and VOC transport from the Port of Itaguaí).

$PM_{2.5}$ levels were higher in the northern district. Both Centro and Maracanã are affected by local vehicular emissions (cars, buses, trucks and motorcycles); Caju and the Port are affected by local vehicular emissions (cars, buses and trucks and also emissions caused by port activities (involving trucks, machines and ship fuel) and marine aerosol. The districts of Vicente de Carvalho, Madureira and Del Castilho are affected by local traffic movements and also by a transport of mixed air masses (vehicular and industrial), and the obtained results are similar to those measured in Irajá (near Vicente de Carvalho and Del Castilho), which is the only fixed automatic monitoring station which measures and reports $PM_{2.5}$ (SMAC 2023a, 2023b).

$PM_{2.5}$ has both primary and secondary origins. Godoy et al. (2018) estimated that secondary particle formation represented between 13.0 and 36.2% of the total concentration in the studied locations. Recently, the Intervention Model for Air Pollution (InMAP) was used to calculate the sources of emissions for 96 global cities (Tessum et al., 2022). In the case of Rio de Janeiro, the modelled results indicated that approximately 30% of fine particulate matter originated from within the city and that the main contributory factors are energy transformation and industrial combustion systems (Tessum et al., 2022). The predictive accuracy of this type of model is not high but the results are useful as a screening device in the absence of experimental data.

Figure 4 – Map of Rio de Janeiro and the studied locations. The areas most affected by ozone and $PM_{2.5}$ are indicated in blue and yellow, respectively.
Source: Google Maps (2023).

Since the complete set of pollutants was only determined in Centro, Vicente de Carvalho, Campo Grande, Bangu (I), Pedra de Guaratiba, Gávea and Maracanã, these locations were chosen to conduct a multivariate analysis and calculate the correlation coefficients. A correlation matrix was created using one value for each day: 24-hour mean values for $PM_{2.5}$ and SO_2, maximum 8-hour mean values for O_3 and CO and a maximum 1-hour mean for NO_2. $PM_{2.5}$ and NO_2 (which are mainly caused by diesel vehicle emissions) show a positive (>60%) correlation in Centro, Campo Grande, Vicente de Carvalho and Maracanã, which suggests that buses and trucks play a significant role in fine particulate matter formation. $PM_{2.5}$ and CO (which are mainly caused by emissions from light-vehicles) show a positive (>60%) correlation in Centro, Gávea and Pedra de Guaratiba, which suggests that cars might play a role in $PM_{2.5}$ formation. In Bangu (western district), the $PM_{2.5}$ correlation with CO and NO_2 was weak, which suggests there might be other factors (probably related to the industrial activities carried out in the western district, largely agriculture, livestock and mining activities). NO_2 and O_3 showed a slightly negative correlation (-20%) in Centro, which confirms that this location (in 2010) had a VOC-limited ozone regime. The correlation coefficients in the other locations were approximately zero, which indicates there is an intermediate (or transition) regime.

Experimental results and Figure 4 show that emission sources (including ozone precursors, VOC and NO_x), transport and meteorological conditions are crucial to understand and control ozone and fine particulate matter levels. The main topographical features and emissions sources were described in Items 2.1 and 2.2. Wind roses were constructed for all the studied locations. Cantagalo and Gávea, in the south, receive winds from the Atlantic Ocean (south, southeast and southwest) and, then, are only affected by local emission sources, caused by heavy traffic (cars, motorcycles and buses). Pedra de Guaratiba and Recreio dos Bandeirantes, in the south-west, are also affected by winds from the Atlantic Ocean, but the vehicular contribution is lower, particularly in the residential area of Pedra de Guaratiba, leading to low NO_2 levels and relatively high VOC/NO_x ratios. Centro, Maracanã and the Port of Rio are affected by air masses from the south and southeast and thus, the main emission sources are local, including marine aerosol from Guanabara Bay. In Bangu and Campo Grande, the

Pedra Branca and Gericinó-Mendanha Massifs prevent air circulation coming from the south and north, and winds from the west and east carry pollutants from the west industrial zone and the main streets, avenues and railways in the north of the city and the MRRJ. As previously stated, Vicente de Carvalho, Madureira and Del Castilho are affected by winds from the north and northeast and also the south and southeast, leading to complex mixed pollutant sources and higher levels of ozone and fine particulate matter.

Since $PM_{2.5}$ is the pollutant of major concern, the AQI were calculated on the basis of this pollutant (the detailed calculations are available as Supplementary Material). In compliance with Brazilian legislation, AQI must be calculated by taking account of all the criteria pollutants (MMA, 2019). In view of this, the calculated values are a lower limit, and the other AQI could be higher, in particular for ozone and PM_{10}, which was not determined by the mobile station (SMAC, 2023c).

As examples of the results, data for Del Castilho were collected in the dry season, and approximately 56% of days had a "good" AQI, in accordance with the guidelines in Brazilian legislation (<25 μg m^{-3}). In Caju, data covered both the dry (June-September) and the rainy (December-April) seasons. "Good" AQI were determined in approximately 55 and 78% of the days, during the dry and the rainy seasons, respectively. Clearly, even in the rainy season, and given the fact that there is a limit of 25μg m^{-3}, fine particulate matter levels are high in this typical northern region of the city and the WHO recommendations of 3–4 exceedance days per year are not met (WHO, 2021).

Air quality management requires prior screening of air quality within the city and an understanding of all the processes leading to the transport and fate of pollutants (both primary and secondary). According to the last report (2021) of the Energy and Environment Institute (IEMA) — a non-profitmaking organization which collects data and information in partnership with Brazilian public environmental agencies — only ten states and the Federal District have any type of air quality monitoring (IEMA, 2021). Moreover, the data compiled in the Air Quality Platform show that the best coverage is achieved in São Paulo, followed by Rio de Janeiro and Minas Gerais. In the case of the city of Rio de Janeiro, the platform compiles data about $PM_{2.5}$ for 15 semi-automated monitoring stations (INEA) and the SMAC automated station (Irajá), and ozone data for 21 INEA station and eight SMAC stations (IEMA, 2022). Fine particulate matter is measured at the semi-automated monitoring stations once every six days using high-volume air samplers. Until April 2023, the municipal and state agencies (SMAC and INEA) publish online the AQI of eight and five fixed monitoring stations located in the city of Rio de Janeiro, respectively (INEA, 2023; SMAC, 2023b). Only one of them (Irajá), operated by SMAC, measures $PM_{2.5}$ by means of automatic continuous equipment (SMAC, 2022b). As previously stated, Brazilian legislation stablished that air quality monitoring and management should be performed by each state government (CONAMA, 2018). Clearly, the monitoring is insufficient when account is taken of the spatial distribution and the number of covered pollutants (IEMA, 2022).

There is considerable evidence that air pollution is one of the greatest risks to health and that the effects are both long- and short-term (OPAS, 2022; WHO, 2022c). Reducing air pollution and, especially, exposure to $PM_{2.5}$ is a key factor to improve public health. Data obtained by the mobile monitoring station and described in this study show that $PM_{2.5}$ levels are high in the north of the city of Rio de Janeiro, and further measures are needed to improve air quality and public health.

In spite of the efforts of the technical staff of both the municipal and state agencies, funding is not sufficient for the installation of new stations and even for the maintenance of the available monitoring network. Nonetheless, monitoring campaigns supported by mobile stations can optimize resources and help to identify which areas are more critical before the installation of expensive fixed stations (which also need significant funding for maintenance and calibration). Mobile air quality monitoring could be used: i) to assess new launch site locations, ii) to fill in the gaps between the fixed stations, iii) to understand the features of an area with multiple pollution sources, and iv) to reduce costs since they could be shared through multiple locations. Unfortunately, this mobile station was deactivated in 2018, owing to a lack of funds.

Conclusions

Data obtained by the SMAC mobile monitoring station provided a useful insight into the state of air quality in the city of Rio de Janeiro. The results described in this study confirm the findings of previous articles, published by several research groups in the area of atmospheric chemistry, as well as reported information about air quality. Clearly, air quality management in the city is a complex task since sources outside the city (in particular from the north of the MRRJ) seems to play a central role in the formation of secondary pollutants. The northern (Del Castilho and Vicente de Carvalho) and western region of the city (Campo Grande, Bangu, Pedra de Guaratiba) are characterized by higher O_3 levels. $PM_{2.5}$ levels were higher in the northern district. Both Centro and Maracanã are affected by local vehicular emissions; Caju and the Port are affected by local vehicular emissions and also emissions caused by port activities and marine aerosol. The districts of Vicente de Carvalho, Madureira and Del Castilho are affected by local traffic movements and also by a transport of mixed air masses (vehicular and industrial) originating in the industrial area. Although most of the AQI are within the "good" classification as defined in Brazilian legislation, when the more recent WHO guidelines are taken into account, levels of $PM_{2.5}$ are high and may represent a serious risk to human health, both as a result of short- and long-term exposure (24-hours and annual). In fact, in the light of the recent evidence compiled by WHO, the Brazilian NAQS needs to be renewed. With regard to air quality management planning (AQMP), account should be taken of the transport system in the whole metropolitan region and, probably, other regions in the state as well. Finally, the contribution of air quality mobile stations should be noted as a flexible and cost-effective way to obtain a preliminary survey of pollutant concentrations, in complex areas with a range of spatial variations and emission sources. This will enable the most critical areas to be detected so that interventions can be concentrated on continuous monitoring and appropriate measures be taken.

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Contribution of authors:

RODRIGUES, J.R.B.A.; DANTAS, G.; SICILIANO, B.: methodology; software; formal analysis; validation; writing-review & editing. DA SILVA, C.M.: Conceptualization; writing original draft; writing-review & editing; funding acquisition; supervision. ARBILLA, G.: conceptualization; methodology; validation; investigation; writing original draft; supervision; writing-review & editing; funding acquisition; supervision.

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