Environ Monit Assess (2019) 191:369
https://doi.org/10.1007/s10661-019-7496-y

Air quality monitoring assessment during the 2016 Olympic Games in Rio de Janeiro, Brazil

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Received: 13 September 2018 / Accepted: 23 April 2019

Abstract In 2009, the city of Rio de Janeiro was announced as the host city of the 2016 Olympic Games (Rio 2016). For this event, the Brazilian government, in partnership with the International Olympic Committee (IOC), undertook the task of monitoring the air quality in the city. This study discusses the PM_{10}, $PM_{2.5}$, and O_3 profiles at ten sampling sites located near the arenas in 2016, including during the Olympic Games period. At all sampling stations, the annual mean values of PM_{10} and $PM_{2.5}$ were below either Brazilian air quality standards or United States Environmental Protection Agency (U.S. EPA) guidelines. In addition, no violations lasting 24 h were observed for particulate matter in 2016. Only two ozone episodes occurred in 2016, both in Campos dos Afonsos (163 and 195 μg m^{-3}) near the extreme sports arena. However, during the pre-Olympic period (2013–2015), in the same area were registered 16, 81, and 18 violations per year, respectively. The results showed an improvement in air quality in Rio de Janeiro in 2016. The reduction in pollutant levels, especially O_3 and $PM_{2.5}$, is probably due to the conclusion of the structural construction of the Olympic arenas and efforts to improve urban mobility.

Keywords Air quality · PM_{10} · $PM_{2.5}$ · O_3 · Olympic Games

Introduction

In 2009, the city of Rio de Janeiro was announced as the host city of the Olympic Games in 2016, known as Rio 2016. This was the first time that a South American and Portuguese-speaking city hosted the Summer Olympics and the third time that the Olympics were held in a city in the Southern Hemisphere (Tsuruta et al. 2017). The city is the second largest in Brazil with an area of 1224 km^2, 6.5 million inhabitants (IBGE 2012), and 3 million vehicles (DETRAN 2014).

Since the 2000 Olympic Games in Sydney, Australia, the International Olympic Committee (IOC) requirements for air quality monitoring have increased

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10661-019-7496-y) contains supplementary material, which is available to authorized users.

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Published online: 16 May 2019

(Ventura et al. 2016). Regional air quality was one of the local organization's priorities and a compromise with the IOC. Fine particulate matter ($PM_{2.5}$) and ozone (O_3) were two parameters of concern due to their relationship with respiratory diseases (Li et al. 2010; Wang et al. 2009; Guo et al. 2013).

In the city of Rio de Janeiro, the Environmental Institute of Rio de Janeiro State (INEA) and the Environmental Department of Rio de Janeiro City (SMAC) are responsible for the air quality monitoring network (SMAC 2013; INEA 2016a). To meet the IOC requirements, INEA installed meteorological and air quality (PM_{10}, $PM_{2.5}$, and O_3) automatic monitoring stations in areas surrounding the Olympic Games competition venues in 2011 (INEA 2016a; Tsuruta et al. 2017; Ventura et al. 2018). These networks were called the Olympic Stations.

Particulate matter (PM) and O_3 are among the six pollutants (PM, CO, Pb, SO_2, NO_2, and O_3) used to assess air quality and avoid damage to health and ecosystems (U.S. EPA 2012). PM is considered a cause of respiratory and cardiac problems (Dominici et al. 2006). Ozone in the stratosphere has beneficial effects on health since it absorbs UV radiation; however, in the lower troposphere, it can have a negative impact on public health (Luna et al. 2014). In high concentrations, these pollutants can reduce athletes' physical capacity and cause discomfort to the public watching the Games as well as the local population (INEA 2016a). Moreover, these pollutants can affect climate on local and regional scales (Twomey 1977; Lv et al. 2016).

Rio de Janeiro has undergone many changes since 2008, mainly in infrastructure and urban mobility, due to the World Cup and Olympic Games. Some of the main improvements include international airport expansion (2008); building a hotel network (2010), especially in the Barra da Tijuca region; and Maracanã Stadium reform (2010). In addition, urban mobility improvements are construction of exclusive bus routes (BRT), which integrate the international airport and the Olympic arenas (2011), and the metro (line 4) (2010), which connects hotels to the Olympic venues (Ventura et al. 2017b; Lindau et al. 2016; Santos and Ribeiro 2015). Although the number of vehicles was not recorded before and after improvements, studies suggest an increase in the number of vehicles traveling through the Olympic arena areas since 2010 (Godoy et al. 2018). According to the State Department of Transit of Rio de Janeiro (DETRAN-RJ), the fleet of vehicles registered in Rio de Janeiro City is approximately three million vehicles. The fleet is composed of 45% of vehicles less than 10 years old and 18% less than 5 years old (DETRAN-RJ 2019). As most of the vehicles are old, many of them do not have a catalyst, which increases the pollutant levels. The fleet profile has almost not changed over the years, with 72–75% of automobiles, 10–12% of motorcycles, 8–10% of trucks, 1–2% of busses, and 2–5% of other motor vehicles.

Considering that the Brazilian market has fuel with a quality comparable to international standards (gasoline S50 and diesel S10), further air quality improvements are expected because of investments in a public transport network and urban mobility programs, which are considered the legacy of the 2016 Olympic Games (Godoy et al. 2018). On the other hand, several studies have shown that traffic restrictions had a limited effect on air quality during the 2008 Olympic Games because other factors, such as weather conditions, also contributed to air quality (Li et al. 2010; Wang et al. 2009; Guo et al. 2013). Notwithstanding, during the Olympic Games, the Rio de Janeiro Government also adopted some policies to reduce vehicular emissions, such as restricting access to all venues exclusively to public transport, restricting driving for vehicles in certain areas and on main avenues, restricting freight deliveries in terms of time and area, and setting holidays in schools and universities (Tsuruta et al. 2017).

The goal of this study is to assess the air quality monitoring results obtained during the 2016 Olympic Games in Rio de Janeiro, Brazil, at the end of the implementation of civil works and urban mobility improvements, which remain as a legacy of the Olympic Games.

Methodology

The city of Rio de Janeiro is on the South Atlantic coast, near coordinates 22° 54′ S and 43° 12′ W, and it is surrounded by the Atlantic rainforest. The Tijuca Forest, which is part of the mountainous Atlantic rainforest, with peaks up to 1021 m (Tijuca Peak), divides the city into northern and southern regions and forms a natural barrier to air circulation (SMAC 2013). In addition, the city has the mountain ranges of the Serra do Mar, such as the Tijuca, Gericinó, and Pedra Branca Massives, which act as physical barriers between the waterfront and the mainland (Martins et al. 2017; Gioda et al. 2011; Silva et al. 2018; Sousa et al. 2012).

For this work, we utilized the Olympic Stations operated by INEA and two stations operated by SMAC (Fig. 1), which were near the Olympic competition sites (Table S1 in the supplementary material), to measure PM_{10}, $PM_{2.5}$, or O_3. Table S2 in the supplementary material presents the localizations and the parameters monitored at each station. This study analyzed data collected in 2016, especially during the 2016 Olympic Games in Rio de Janeiro, which occurred from 5 to 21 of August during the winter in Brazil.

The air quality monitoring stations were distributed in four Olympic Games regions: Barra da Tijuca (Recreio dos Bandeirantes station), Deodoro (Gericinó and Campo dos Afonsos stations), Copacabana (Lagoa, Leblon, Urca, and Copacabana stations), and Downtown (Downtown and Maracanã stations). The micro-siting description for all stations is presented in Table S2 (Supplementary Material).

The automatic stations take continuous hourly average measurements of the O_3 and PM_{10} concentrations. The semiautomatic stations monitor the particulate matter ($PM_{2.5}$ and PM_{10}) concentration in the air for 24 h every 6 days (INEA 2016a) simultaneously at each sampling site, similar to the standard established by U.S. EPA in Section 58.13, Subchapter 58, Chapter 40, of the Federal Code regulations (40 CFR 58, Section 58.13). The automatic stations are calibrated monthly, following the procedures described in the equipment manufacturer's manuals. For ozone, the calibration is done with the air totally free of the pollutant and adjusting its value to 0. Subsequently, a gas with a known concentration is sampled and the instrument is regulated to this concentration. The semiautomatic stations are calibrated according to the ABNT 13412 method (1995). The standard consists of the calibration of the sampler flow indicator device, in order to relate the flow measurements to a primary standard. A flow pattern calibrator, calibrated against a standard primary volume meter, is used to calibrate or verify the accuracy of the sampler flow indicator device. The mass concentrations of particulate matter in the atmosphere are calculated using flow rates corrected for standard conditions of temperature and pressure.

The particulate matter samples were collected by INEA in the semiautomatic stations using high-volume samplers (Model AGVMP252, Energética, Brazil, for $PM_{2.5}$ and Model AGVMP10, Energética, Brazil, for PM_{10}). These samplers, placed 3 m above ground level, retained the PM in glass-fiber filters (Millipore, USA) with a volumetric flow rate of 0.019 $m^3\ s^{-1}$. The mass of PM was obtained by gravimetric analysis. The filter mass was weighed before and after collection on an analytical balance (Mettler E., Zürich. Switzerland, ± 0.0001 g), as described in the Brazilian Technical Standard (NBR 13412) method, which is similar to the ASTDM-D4096 method. PM_{10} was also monitored by SMAC using a Met One Instruments particulate monitor BAM 1020 model, which measured the concentrations every 1 h.

Finally, ozone monitoring by INEA followed the U.S. EPA Reference Method EQOA-0506-160 and was performed with the equipment O342M, Environment S.A., France. Ozone was also monitored by SMAC using an Ecotech PTY Serinus 10 model, which measured the concentrations every 15 min.

To better understand the air quality levels, meteorological data, such as temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WD), were also measured (Table S3, Supplementary Material). The meteorological data are the hourly averages calculated every 15 min obtained by automated analyzers (Met One Instruments, TX, USA) at surface meteorological stations located near the sampling sites ($d < 2$ km). The meteorological data used in the statistical analyses were averages over 24 h, except WD, which was calculated from the mode and is shown by wind roses (Figure S1, Supplementary Material). The wind roses present different behaviors, since they belong to different places of the city of Rio de Janeiro, such as south and north zones and downtown, and they have micro-siting specifics (Table S2). In addition, the influence of thermal inversion phenomenon on pollutant behavior in August (2015 and 2016), at the Downtown and Copacabana stations, was verified. The thermal inversion was identified from interpretation of radiosonding data from Galeão Airport. Thermal inversion was observed for 20 days in August 2015 and 13 days in August 2016. According to the Köppen climate classification scheme, the climatic condition of Rio de Janeiro belongs to group A, i.e., tropical megathermal and Atlantic tropical (Aw). The average temperatures vary between 23 and 25 °C, where January is the warmest month, with an average of 27 °C, and

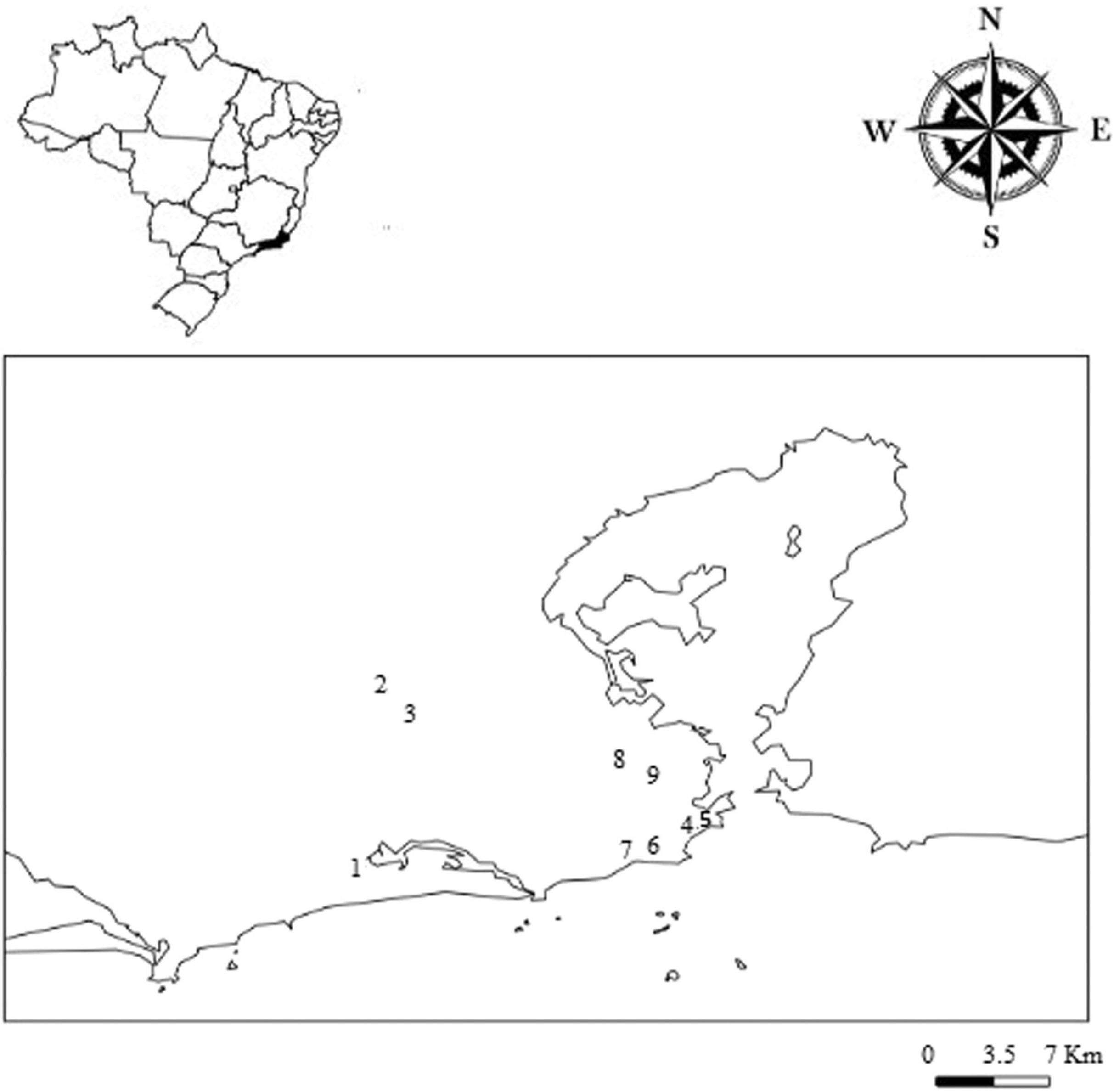

Fig. 1 Map of Olympic Stations distributed in relation to the Rio 2016 competition venues: 1—Recreio dos Bandeirantes, 2—Gericinó, 3—Campos dos Afonsos, 4—Copacabana, 5—Urca, 6—Leblon, 7—Lagoa, 8—Maracanã, 9—Downtown. Font: adapted from Ventura et al. (2018)

July is the coldest, with an average of 21 °C. The annual relative humidity varies between 65 and 80%, with no significant variation during the year. The total accumulated annual rainfall is generally representative of a rainy season (from October to March) and a dry season (from April to September). The rainfall difference between the driest and the wettest months is approximately 94 mm. The wind speed is usually less than 2 m s^{-1}, which does not favor atmospheric dispersions. In addition, air circulation in the metropolitan area is significantly affected by topographical conditions (FEI 2017).

To verify the correlation between the pollutants measured in the Olympic Games regions and the meteorological data, a correlation matrix was used. This technique was applied to the data of PM_{10}, $PM_{2.5}$, O_3, T, RH, and WS for the average daily data of pollutant concentrations and meteorological parameters, except for ozone, which adopted the maximum daily concentration.

Results and discussion

In Brazil, the air quality standards are set by the Environment Council National through Resolution no. 03, which was published in 1990 (CONAMA 1990). In Brazilian legislation, the annual mean PM_{10} concentration standard is 50 μg m^{-3}, and the daily average concentration standard is 150 μg m^{-3}; for O_3, the hourly concentration standard is 160 μg m^{-3}. Brazilian legislation has not been updated since its creation in the 1990s. Presently, this resolution is being reviewed, and the limits for $PM_{2.5}$ will be included, as $PM_{2.5}$ is considered one of the most common atmospheric pollutants in the world. According to epidemiological studies, $PM_{2.5}$ can be inhaled and absorbed by the lungs, causing adverse effects on human health and increasing cardiopulmonary mortality and morbidity (Moura et al. 2009). Due to the lack of national $PM_{2.5}$ standards, in this study, we used the National Ambient Air Quality Standards (NAAQS) set by U.S. EPA to evaluate the results, because these standards include health criteria and socioeconomic aspects. For a short-period exposure, a daily standard of 35 μg m^{-3} was adopted. For a long-period exposure, an annual standard of 12 μg m^{-3} was adopted.

Ozone

Ozone is the most abundant pollutant monitored by the air quality network in Rio de Janeiro (INEA 2016a). As already documented, high O_3 concentrations adversely affect human health, agriculture, and materials (Parrish et al. 2011; Arsic et al. 2011; WHO 2008). In addition, increased O_3 concentrations in the troposphere induce numerous and highly severe health effects (WHO 2008).

In Rio de Janeiro, there are automatic devices that provide data on the O_3 hourly average concentration. Because of that, it is possible to notice cycles during the day and night and identify large variations registered throughout the day, especially during peak hours when the values are usually higher than the daily average concentration. Thus, it is expected that higher concentrations of this pollutant will be observed during the afternoon, due to an occurrence of favorable meteorological conditions for the formation of the pollutant in the atmosphere. Figure 2 shows the O_3 hourly profiles during the Olympic Games. Overall, the O_3 profile was similar to all sites, with the highest concentrations measured from 1:00 PM to 5:00 PM and the lowest concentrations in the early morning. Ozone formation is directly related to solar radiation and volatile organic compound (VOC) and nitrous oxide (NO_x) levels. The highest NO_x levels and solar radiation incidence occur in the afternoon (INEA 2016a). After that, the O_3 concentrations began to decrease due to the reduced amount of sunlight, as the consumption processes prevail over the formation processes.

In the Deodoro region, we observed the lowest O_3 concentrations at dawn. The low levels are probably due to truck traffic (INEA 2016b). This kind of vehicle emits a large amount of NO_x, which consumes the residual O_3 formed in the afternoon of the previous day (Martins et al. 2015). In addition, in this zone, there are topographical blocks, which accumulate the ozone near this avenue.

In the Copacabana, Barra, and Downtown regions, there is light traffic from 10:00 PM to 8:00 AM. In addition, the largest circulation in this region is due to light vehicles. Thus, there is no significant consumption of O_3 in these regions, and the levels do not vary during dawn.

From Table 1, it is possible to verify some positive correlations between O_3 and T. According to a study by Silva et al. (2016), although the process of O_3 formation is initiated photochemically, the correlation is also high for temperature. This fact is justified because solar radiation and temperature are two meteorological parameters that are interconnected and highly correlated. On the other hand, a negative correlation between O_3 and RH was observed. The negative value means that these variables are inversely proportional, because as the temperature increases, an expansion in air volume occurs, resulting in a decrease in relative humidity. Due to that, in all Olympic Games regions, T and RH showed a negative correlation. A relationship between maximum hourly concentrations (August 2015/2016) and thermal inversion was not observed, probably due to low solar radiation during winter which leads to less ozone formation.

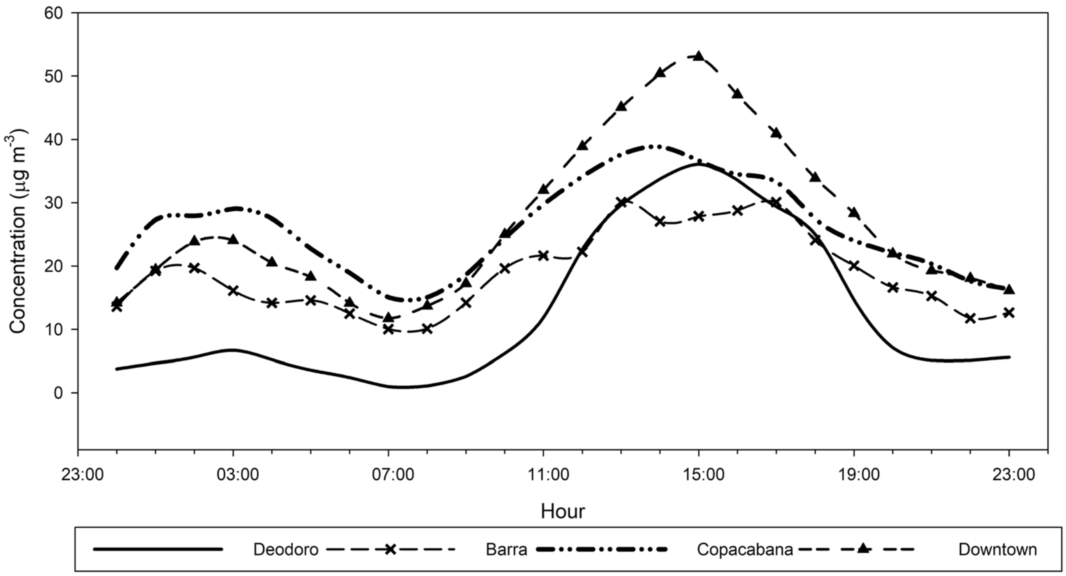

Fig. 2 Hourly average O_3 concentration by sporting regions during the 2016 Olympic Games

During the Olympic Games, the hourly maximum O_3 concentration measured at the monitoring stations varied from 67 to 100 µg m^{-3} (Table 2), which does not exceed the Brazilian air quality standard (160 µg m^{-3}), as was expected. A similar behavior was observed in previous years (2013, 2014, and 2015) during August, where the concentrations did not exceed 150 µg m^{-3} (Ventura et al. 2018). It is well known that O_3 concentrations do not exceed air quality standards in wintertime. Though O_3 is the pollutant with the most violations to national air quality standards in Rio de Janeiro (Martins et al. 2015; Silva et al. 2016), in 2016, only two occurrences were registered. Both O_3 episodes occurred in Campo dos Afonsos (Table 2). The first (195 µg m^{-3}) happened on February 20 at 5:30 PM, and the second (163 µg m^{-3}) occurred on April 16 at 2:30 PM. According to Finlayson-Pitts and Pitts (2000), O_3 episodes usually occur during sunny days, where strong solar radiation and high temperatures favor the reactions that lead to O_3 formation and various other oxidizing species. Previously, 34, 111, and 49 violations were registered from 2013 to 2015, respectively (Ventura et al. 2016).

Figure 3 shows the monthly maximum hourly O_3 concentrations in each Olympic Games region during 2016. The highest concentrations were measured in February, where the highest temperatures were also registered that year. According to Silva et al. (2016), solar radiation and temperature are interconnected meteorological parameters with a high positive correlation. In previous years, summer was also the period that showed the highest maximum O_3 concentrations. According to Ventura et al. (2018), this occurs in subtropical climate regions, such as Rio de Janeiro, due to high temperatures and incidence of solar radiation, but on the other hand, there was low cloud formation and a low volume of rainfall.

The Deodoro region usually presented the highest hourly O_3 concentrations in the atmosphere in relation to the other regions studied during 2016 (Fig. 3). At this site, high concentrations of the precursors (NO_x and VOC) of this gas are emitted by vehicles in the most polluted road in Rio de Janeiro state, located in Deodoro. Moreover, Mendanha Mountain and Pedra Branca Forest make it more difficult to disperse the pollutants.

Due to the economic crisis in the state of Rio de Janeiro, some air quality monitoring stations operated by INEA presented operational problems due to lack of maintenance. Therefore, some data is missing in the time series, e.g., November and December in Barra da Tijuca and Deodoro regions.

Ozone showed a negative correlation with $PM_{2.5}$ and PM_{10} in all Olympic Games regions (Table 1).

Table 1 Correlation matrix of meteorological variables (WS, T, and RH) and atmospheric pollutants ($PM_{2.5}$, PM_{10}, and O_3) for each Olympic Games region in 2016

Olympic Games regions	Variables	O_3	$PM_{2.5}$	PM_{10}	WS	*T*	RH
Barra	O_3	1.00					
	$PM_{2.5}$	− 0.17	1.00	–			
	WS	− 0.11	− 0.20	–	1.00		
	T	0.16	− 0.13	–	0.18	1.00	
	RH	− 0.11	− 0.27	–	− 0.16	*− 0.30*	1.00
Copacabana	O_3	1.00					
	$PM_{2.5}$	*− 0.72*	1.00				
	PM_{10}	*− 0.31*	*0.30*	1.00			
	WS	0.23	0.05	*0.43*	1.00		
	T	*0.35*	0.09	*0.41*	0.16	1.00	
	RH	− 0.09	− 0.20	− 0.28	*− 0.33*	− 0.20	1.00
Deodoro	O_3	1.00					
	PM_{10}	− 0.24	–	1.00			
	WS	− 0.05	–	− 0.15	1.00		
	T	*0.59*	–	0.06	0.19	1.00	
	RH	*− 0.38*	–	*− 0.32*	− 0.20	*− 0.45*	1.00
Downtown	O_3	1.00					
	$PM_{2.5}$	*− 0.63*	1.00				
	PM_{10}	*− 0.51*	*0.50*	1.00			
	WS	0.02	− 0.17	− 0.28	1.00		
	T	*0.37*	0.11	− 0.04	0.09	1.00	
	RH	*− 0.37*	− 0.29	*− 0.40*	0.06	*− 0.43*	1.00

The italicized values are statistically significant, 95%

According to Martins et al. (2015), although PM does not directly participate in the process of ozone formation, environments with higher PM concentrations block solar radiation due to light scattering and decrease the photochemical dissociation of NO_2. This photochemical dissociation of NO_2 initiates the process of ozone formation by forming atomic oxygen.

Table 2 Descriptive statistics for O_3 in Rio de Janeiro in 2016 and during the Olympic Games

Monitoring stations	Olympic Games regions	In 2016			During the Olympic Games		
		N	Max (μg m^{-3})	SD (μg m^{-3})	*N*	Max (μg m^{-3})	SD (μg m^{-3})
Lagoa	Copacabana	4850	146	22	217	76	21
Leblon		5775	93	13	408	75	14
Copacabana		8127	130	15	405	67	16
Maracanã	Downtown	7797	124	19	408	100	21
Downtown		8399	159	20	405	88	21
Campo dos Afonsos	Deodoro	5889	195	24	408	80	16
Recreio dos Bandeirantes	Barra	5148	130	19	402	94	18

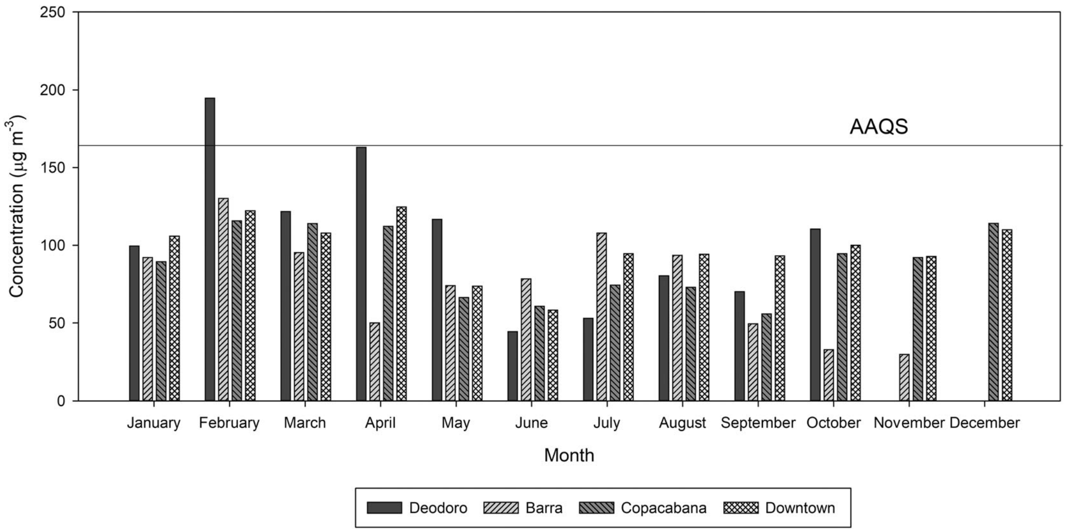

Fig. 3 Comparison between monthly maximum hourly O_3 concentrations by sporting regions in 2016 and Brazilian ambient air quality standard (AAQS)

PM_{10}

In 2016, the annual average PM_{10} concentration varied from 30 to 40 μg m^{-3} in the Olympic regions, except at the Copacabana station, where the average (61 μg m^{-3}) (Table 3) exceeded the annual air quality limit set by Brazilian standards (50 μg m^{-3}). However, these values were very similar to those observed in Athens, Greece, in 2004 (30–60 μg m^{-3}) (Gryparis et al. 2014) and much smaller than those registered in Beijing, China, in 2008 (73–152 μg m^{-3}) (He et al. 2016).

The average PM_{10} concentrations registered during the Olympic Games varied from 45 to 64 μg m^{-3} (Table 3), which were very similar to those registered in August of the previous 3 years (2013, 2014, and 2015) at the Olympic Stations (Ventura et al. 2016). On the other hand, during the 2008 Olympic Games in Beijing, China, the average PM_{10} concentration was reduced by 35% in relation to the recorded pre-Olympic period (Tsuruta et al. 2017), reaching 54 μg m^{-3}. This reduction occurred because the Chinese government banned the use of coal during the Games (He et al. 2016). In Rio de Janeiro, besides traffic restrictions, no additional strategies were implemented to reduce pollutant emissions.

Recently, Ventura et al. (2018) reported that the daily PM_{10} levels (24-h average) in the Copacabana, Maracanã, and Deodoro regions in 2013–2015 ranged from 6 to 96 μg m^{-3}. In 2016, the concentrations varied from 3 to 113 μg m^{-3}. Although the Downtown and Copacabana stations registered (Table 3) the highest daily PM_{10} concentrations in 2016 (102 and 113 μg m^{-3}), they did not surpass the daily air quality limit set by Brazilian standards (CONAMA 1990) or American standards (US.EPA 2012), which corresponds to 150 μg m^{-3}. A correlation was observed between thermal inversion and PM_{10} levels (24-h average). The days with inversion showed a global average at least 14% higher than those ones without the meteorological phenomenon presence.

At the Maracanã station, the annual average PM_{10} concentration decreased significantly during the sampling period (1998–2013), although the concentration was below the air quality standard (50 μg m^{-3}) in most years (Gioda et al. 2016). However, in the same place in 2014 and 2015, the concentration of this pollutant increased (58 and 61 μg m^{-3}). Most likely, this occurred due to infrastructure development in the city for the sporting events, such as restructuring civil works in Maracanã Stadium to meet the standards set by IOC so the stadium could host the sportive competitions and the Games' opening and closing ceremonies (Ventura et al. 2016). The same happened in Athens, where this phenomenon was associated with a significant increase in civil works (buildings, roads, sportive installations, etc.) for the 2004 Olympic Games, which may have caused an increase in PM_{10} levels by the emission or resuspension of dust by the heavy vehicles that worked on the construction (Vassilakos et al. 2005).

Table 3 Descriptive statistics for PM_{10} and $PM_{2.5}$ in Rio de Janeiro in 2016 and during Olympic Games

Pollutants	Monitoring stations	Olympic Games regions	In 2016					During the Olympic Games				
			N	Max ($\mu g\ m^{-3}$)	Min ($\mu g\ m^{-3}$)	SD ($\mu g\ m^{-3}$)	Mean ($\mu g\ m^{-3}$)	*N*	Max ($\mu g\ m^{-3}$)	Min ($\mu g\ m^{-3}$)	SD ($\mu g\ m^{-3}$)	Mean ($\mu g\ m^{-3}$)
$PM_{2.5}$	Recreio dos Bandeirantes	Barra	55	36	2	7	10	3	17	8	5	13
	Maracanã	Downtown	45	95	3	15	11	1	29	29	–	29
	Copacabana	Copacabana	23	29	3	8	11	1	23	23	–	23
	Urca		40	23	3	5	8	3	23	8	8	13
	Lagoa		49	28	1	5	10	1	28	28	–	28
PM_{10}	Campo dos Afonsos	Deodoro	49	69	13	14	32	3	64	20	23	45
	Gericinó		41	99	14	20	40	3	99	13	38	45
	Carioca*	Downtown	349	102	3	14	30	18	80	11	17	37
	Copacabana*	Copacabana	342	113	30	14	**61**	18	101	45	14	64

*Automatic air quality monitoring station

PM_{10} showed a negative correlation with RH, most likely due to humidity deposition. As the relative humidity increases, PM_{10} in the air tends to bind to adjacent particles, increasing the mass, and consequently undergoes deposition.

Monthly data of particulate matter are a good indicator of atmospheric pollution, not only because the data show a direct standard measure for the concentration of dust in the air but also because of the direct relation to human health (Leys et al. 2011). Figure 4 presents the monthly average PM_{10} concentration in each Olympic Games region in 2016 to elucidate the particulate matter behavior during different seasons, especially in winter, when the Rio 2016 occurred.

The highest average PM_{10} concentrations in Deodoro and Downtown were registered in July, during the winter, where the most critical atmospheric pollution conditions are generally observed (Ventura et al. 2018). The PM_{10} seasonality was also studied by Gioda et al. (2016), who previously verified, through time series analysis based on a 50-year database of this pollutant in Rio de Janeiro, that there was an increasing trend during the winter (June–August), which corresponds to the period with lower precipitation and air mass stagnation. One of the first health studies performed in Rio de Janeiro evaluated the relationship between suspended particulate matter levels and respiratory diseases, and it showed a prevalence of more frequent hospital emergency cases during the winter (Brilhante and Tambellini 2002).

During 2016, in Copacabana, higher pollution levels (63 $\mu g\ m^{-3}$) were recorded in August, while lower pollution levels were found in May and June (Fig. 4), which was not expected for this period. According to SMAC (2013), the Copacabana station presents a peculiar characteristic that is different from the other stations, because this station is highly influenced by vehicular traffic, as it is installed too close to a bus stop; in addition, it is in a canyon surrounded by tall buildings, so particulate material and other polluting gases emitted mainly by light vehicles and busses are confined within. Looking at the data from the Copacabana station in previous years, the PM_{10} seasonality is almost constant throughout the year.

Some researchers have already been studying PM_{10} results monitored at the Copacabana station. According to Torraca et al. (2012), when the winds had the south direction (coming from the ocean) and it had high speeds, the highest PM_{10} concentration levels were

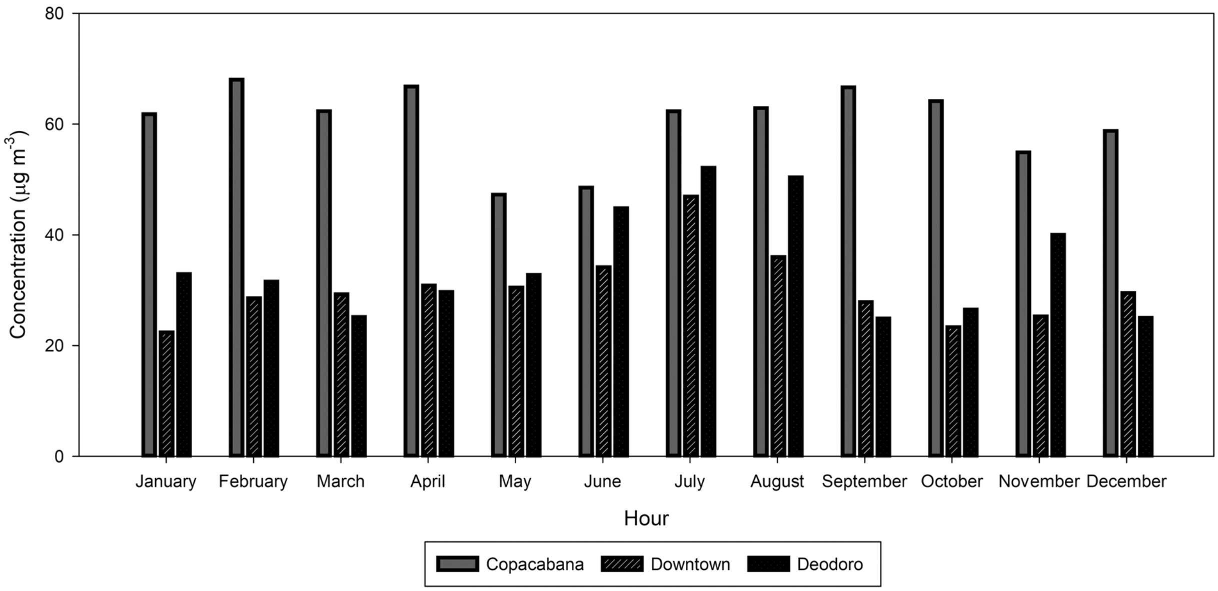

Fig. 4 Monthly average PM_{10} concentration in each Olympic Games region in 2016

verified. Therefore, the researcher concluded that much of these particles were derived from sea salt, given that the region operates low pressure systems that lead to south wind occurrences, carrying marine spray from the ocean to this station. Besides, Soares et al. (2018) attributed also the PM_{10} concentrations from this sampling point to the soil resuspension, since there is a bus stop next to the monitoring station, which justifies the low $PM_{2.5}/PM_{10}$ rate at this site (18%).

According to Ventura et al. (2018), during the pre-Olympic period (2013–2015), the Downtown region showed an average PM_{10} concentration of 51 µg m^{-3} in August. However, in 2016, this same region showed a low pollution level (37 µg m^{-3}) (Fig. 4), most likely because of restrictions on vehicular flux and the holiday period in schools and universities during the Olympic Games (Tsuruta et al. 2017).

$PM_{2.5}$

In the last 10 years, the number of studies on $PM_{2.5}$ increased, as have studies on the chemical composition of this fine particulate material (Ventura et al. 2017b; Godoy et al. 2018). According to Godoy et al. (2018), the vehicular contribution represents 60% of the $PM_{2.5}$ concentration. Ventura et al. (2017b) conducted an exploratory $PM_{2.5}$ study at 15 different RMRJ stations in 2011, including Downtown, Maracanã, Copacabana, and Recreio dos Bandeirantes. Copacabana is a region that suffers interference from vehicle emissions, but because it is located near the sea, it is influenced by the breeze phenomena, which helps the dispersion of atmospheric pollutants, contributing, on the other hand, with the sea spray (Ventura et al. 2017b). According to Quiterio et al. (2004), the main activities developed at the Downtown are administrative and commercial, with the main source of emission being the vehicle exhausts. Downtown, Maracanã, and Recreio dos Bandeirantes had previously been evaluated by Soluri et al. (2007) and Godoy et al. (2009). In all these points, the concentrations of metals were higher in 2011 when compared to the studies carried out by Ventura et al. (2017b), particularly, in Maracanã, whose main sources are light vehicles and busses.

Table 3 presents the $PM_{2.5}$ annual averages measured in 2016. The values ranged from 8 to 11 µg m^{-3}. These concentrations are slightly lower than those measured in the pre-Olympic period (2013–2015), which ranged from 6 to 20 µg m^{-3} (Ventura et al. 2018), and in Buenos Aires, Argentina (15 µg m^{-3}), and Santiago, Chile (30 µg m^{-3}), which are Latin American countries in a similar phase of economic development as Brazil (Jhun et al. 2013; Arkouli et al. 2010). The reduction in $PM_{2.5}$ levels in 2016 is related to the implementation of a more efficient model of public transport, such as Bus Rapid Transport (BRT), Bus Rapid Service (BRS) road corridors, and the subway line. These measures

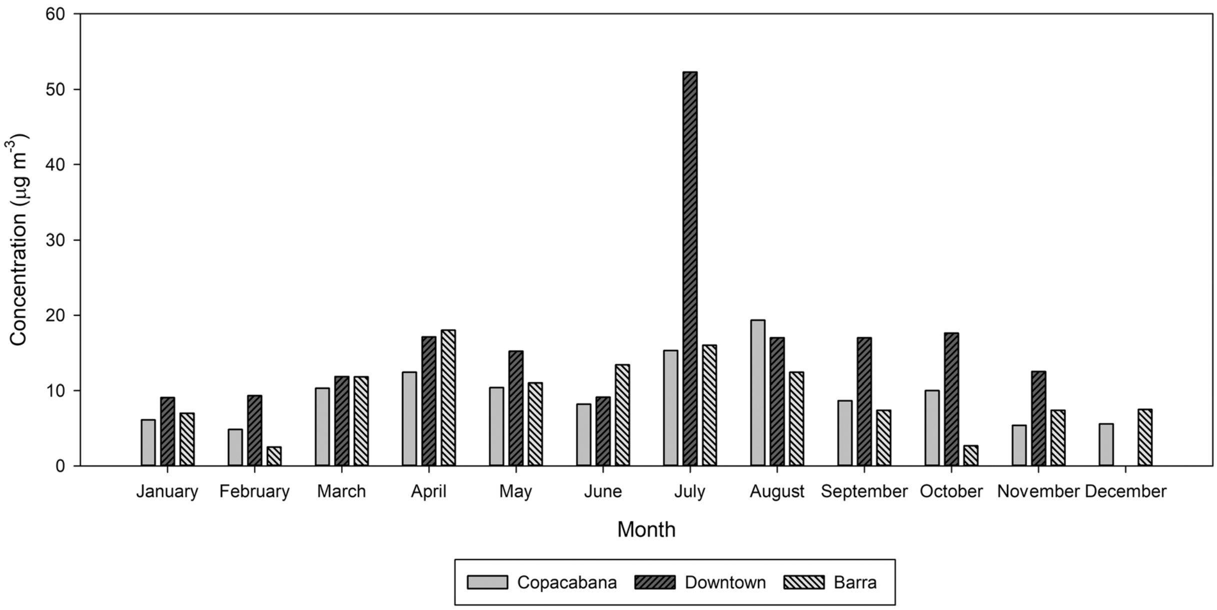

Fig. 5 Monthly average $PM_{2.5}$ concentration in each sportive region in 2016. There was no sampling in the Downtown region in December

reduce the number of vehicles on the street and traffic jams, resulting in lower pollutant levels (Godoy et al. 2017; Lindau et al. 2016).

During the Olympic Games period (August 5 to 21, 2016), $PM_{2.5}$ daily concentrations in Rio de Janeiro City ranged from 8 to 29 μg m^{-3} (Table 3), which did not exceed the U.S. EPA guidelines (35 μg m^{-3}). These results were very similar to those registered in August in the pre-Olympic period (2013, 2014, and 2015) (Ventura et al. 2018). However, in the Maracanã, Copacabana, and Lagoa stations, the samples ($N = 1$) were lower than necessary to represent the period. According to the standard established by U.S. EPA (40 CFR 58, Section 58.13), the high-volume samplers (semiautomatic stations) must operate standardly, monitoring particulate matter every 6 days, and for which there is representation of the monthly average, a minimum of 3 monthly data is required. In these monitoring stations, the access was restricted during the Olympics, which resulted in a smaller number of samples planned during the event period sports ($N = 3$).

This was different from the results obtained in Beijing 2008, where a reduction of 65% of the $PM_{2.5}$ concentration was observed in the Olympic Games period compared with the pre-Olympic period (Li et al. 2010). According to Wang et al. (2010), the decrease in the $PM_{2.5}$ levels in Beijing was due to traffic control. These smaller particles can be deposited in the respiratory tract and, during physical practice, can come to be five times more abundant than those registered when the body is resting (Daigle et al. 2003).

In 2016, the $PM_{2.5}$ daily concentration varied from 1 to 29 μg m^{-3} in the Copacabana region and from 3 to 95 μg m^{-3} in Maracanã, resulting in three violations of the EPA guidelines (US.EPA 2012). Two violations were recorded in July (85 μg m^{-3} and 95 μg m^{-3}), the month before the opening of the Olympic Games and therefore intensified civil works in the Maracanã Stadium, and one in October (41 μg m^{-3}). In addition, one exceedance was observed at the Recreio dos Bandeirantes station in April (36 μg m^{-3}). According to Ventura et al. (2016), the $PM_{2.5}$ daily concentrations in 2013 to 2015 ranged from 1 to 44 μg m^{-3} in the Barra da Tijuca and Copacabana regions, and in the Maracanã region, concentrations ranged from 2.5 to 87 μg m^{-3}. These concentrations are similar to those in 2016.

The results from the Urca station in 2016 (Table 3) showed the lowest annual $PM_{2.5}$ concentration, similar to that verified by Ventura et al. (2016) during the pre-Olympic period. The low levels are because this sampling point is more distant from vehicular influences.

Soluri et al. (2007) and Godoy et al. (2009) evaluated the $PM_{2.5}$ concentration in Recreio dos

Bandeirantes from 2003 to 2005. In the first studies, the annual average concentration was nearly 7.7 μg m^{-3}. Since 2008, the air quality at this site has been influenced by the larger heavy vehicle fleet, mainly due to the construction of an expressway for bus circulation (BRT-TransOeste) connecting Barra da Tijuca to Santa Cruz and construction of an Arena (Sport Parks) and Athletic Villages for the Olympic Games (Ventura et al. 2017a, b). For this reason, this concentration changed from 11 to 16 μg m^{-3} in 2013–2015 (Ventura et al. 2018) and began to reduce in 2016 to 10 μg m^{-3} (Table 3) when all civil works were finished.

In the Downtown and Copacabana regions, which monitored $PM_{2.5}$ and PM_{10} (Table 1), a positive correlation was observed (0.3–0.5). According to Silva et al. (2016), this result indicates that these data probably have the same emission sources.

Figure 5 presents the monthly average $PM_{2.5}$ concentration in each sportive region in 2016. Lower $PM_{2.5}$ concentrations were measured in January and February, during the summer, which is associated with intense rainfall.

The Copacabana region showed the highest $PM_{2.5}$ level (19 μg m^{-3}) in August, as expected, due to the unfavorable conditions for atmospheric pollutant dispersion in this period.

A high average $PM_{2.5}$ concentration was recorded in the Downtown region in July due to the results observed at the Maracanã station (of 85 and 95 μg m^{-3}), which is adjacent to Maracanã Stadium. This occurred because infrastructure works for this stadium were intensified 1 month before the start of the Olympic Games, with works occurring 24 h/day, which also used power generators. In addition, this stadium was used for the opening ceremony.

Conclusion

Although Rio 2016 occurred during the meteorologically unfavorable period to disperse atmospheric pollutants (winter), the criterion pollutants (PM_{10}, $PM_{2.5}$, and O_3) monitored in the sportive regions did not exceed Brazilian or American air quality standards. In addition, as previously predicted by some researchers, air pollution levels in Rio de Janeiro were reduced in 2016, especially O_3 and fine particulate matter ($PM_{2.5}$). This decrease is credited to the conclusion of the structural works to Olympic arenas and urban mobility improvement to accommodate the Olympic Games in the city and the reduction of heavy trucks on the roads to meet this demand, which increased the amount of NO_x and particulate matter released into the atmosphere during the pre-Olympic period (2013–2015). However, the air quality is expected to improve even more in a few years with increasing population adherence to the developed modes of transport (BRT, BRS, and subway), which have become a legacy of the Olympic Games, and the reduction of individual vehicles in circulation.

Acknowledgments The authors are grateful to the Environmental Institute of Rio de Janeiro State (INEA) and the Environmental Department of Rio de Janeiro City (SMAC) for the data.

Funding information This study received financial support from FAPERJ and CNPq.

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