

## Air Quality Indexes in the City of Rio de Janeiro During the 2016 Olympic and Paralympic Games

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In this work, the air quality indexes (AQIs) determined in Rio de Janeiro from July to September 2016, before and during the Summer Olympic and Paralympic Games, in the monitoring stations operated by the Municipal Secretariat of the Environment, were compiled and analyzed. Only four automatic monitoring stations determined all the Brazilian criteria pollutants (smog, total particulate matter, PM<sub>10</sub> (particulate matter < 10 mm), NO<sub>2</sub>, ozone and SO<sub>2</sub>). NO<sub>2</sub> and PM<sub>10</sub> levels were generally lower during the Olympic period because of restrictions on vehicular flux. However, ozone concentrations remained high, due to unfavorable meteorological conditions. The worst conditions were observed in Bangu and Irajá Districts, where ozone concentrations frequently exceeded 160 mg m<sup>-3</sup>. According to the World Health Organization (WHO), as ozone concentrations increase above this value, health effects became increasingly numerous and more severe. Brazilian air quality allowable standards are clearly higher than WHO guidelines, which, in addition to the combined results of the adopted air quality indexes and the use of a restricted number of criteria pollutants to report the air quality, led to AQIs in the intervals good and moderate, despite concentrations frequently being high in terms of WHO guidelines.

**Keywords:** air quality index, Olympic Games, Rio 2016, ozone, PM<sub>10</sub>

### Introduction

A major consideration in bidding to host a major multi-sport event, such as the Olympic Games, is the potential for the event to generate a wide range of benefits for the population of the host city. Such purported benefits, collectively termed as “Olympic legacy”, include improvements in the economy, infrastructure, environment, sports provision and a perspective of sustainable development and investments in transport and public health.<sup>1</sup>

When Rio de Janeiro, endorsed by the Brazilian Olympic Committee (COB), submitted its application to host the Games of the XXXI Olympiad to be held in 2016, the citizens had the hope that the event could lead to positive changes and legacies in the social, economic and environmental spheres.<sup>1</sup>

On October 2, 2009, Rio de Janeiro was announced as the host city of the 2016 Summer Olympic Games, commonly known as Rio 2016. It 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 Southern Hemisphere city. The Olympic Games were held from 5 to 21 August and the Paralympic Games from 7 to 18 September 2016.

During Rio 2016, the city hosted 1.17 million tourists (35% from other countries). The Brazilian Ministry of Tourism reported that the Olympic Games helped the country to achieve record tourism figures in 2016. Over the twelve months of 2016, Brazil welcomed 6.6 million foreign tourists, which represented a 4.8% increase over the previous year and generated a revenue increase of 6.2%.<sup>2</sup>

Rio de Janeiro invested in several infrastructure projects to improve its transport and port region.<sup>3</sup> The competition venues were clustered in four zones: Barra da Tijuca, Copacabana, Deodoro and Maracanã.<sup>4</sup>

In 2011, the Rio de Janeiro State Government approved the “Olympic Project” with the objective of increasing the number of automatic monitoring stations and informing the athletes and population of meteorological and air quality conditions. Historical data reported by the State Environmental Agency (INEA),<sup>5</sup> and the Municipal

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Department of the Environment (SMAC),<sup>6</sup> have shown that in the city of Rio de Janeiro, NO<sub>2</sub>, particulate matter < 10 mm (PM<sub>10</sub>) and ozone are of major concern; however, in the eleven new stations that were installed in the proximity of the Olympic arenas, only the meteorological parameters, PM<sub>10</sub> and ozone concentrations were determined.<sup>7</sup>

Recently, Ventura *et al.*<sup>7</sup> reported that the PM<sub>10</sub> levels (24 h mean) in Copacabana, Maracanã and Deodoro in 2013-2015 were in the range of 6-96 mg m<sup>-3</sup>. These values are below the Brazilian and the United States Environmental Protection Agency (US EPA) standards (150 mg m<sup>-3</sup>) but above the European Union (EU) and World Health Organization (WHO) standards (24 h mean, 50 mg m<sup>-3</sup>).<sup>8-13</sup> In Maracanã, the automatic monitoring station annual means in 2014 and 2015 were 58 and 61 mg m<sup>-3</sup>, respectively, which is higher than the annual national standard (50 mg m<sup>-3</sup>).<sup>8</sup> Ozone concentrations from 2013-2015 were also higher in Deodoro, Maracanã and Copacabana, where the national standard (160 mg m<sup>-3</sup>, mean for 1 h) was exceeded, mainly in the spring and summer, when values as high as 200 mg m<sup>-3</sup> were obtained.<sup>7</sup> It is worth noting that the national standard is higher than the values recommended by the EU and the WHO (78.5 and 98 mg m<sup>-3</sup>, respectively).<sup>9,11,12</sup> The 2013-2015 data suggested that the Deodoro and Maracanã zones were the most important with respect to PM<sub>10</sub> and ozone concentrations. In the same period, Barra da Tijuca pollutant concentrations were below the national standards.<sup>7</sup>

During the event and in the days before and after the Olympic Games, the 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. The most severe restrictions were applied in August, during the Olympic Games (5 to 21 August) and the weeks before and after the Games.

During the Games, the air quality was monitored through the automatic monitoring stations of the State<sup>5</sup> and Municipal Government,<sup>6</sup> and the results were reported to the population in the form of air quality indexes (AQIs). The Brazilian criteria pollutants are smoke, particulate matter, PM<sub>10</sub>, SO<sub>2</sub>, CO, ozone and NO<sub>2</sub>.<sup>8</sup> To comparatively assess the degree of air pollution, the AQI system was proposed by the São Paulo State Environmental Agency (CETESB)<sup>14</sup> and is calculated using the combined concentrations of PM<sub>10</sub>, SO<sub>2</sub>, CO, ozone and NO<sub>2</sub>. The index has a five-step scale, from good air quality (0-50) to extremely high pollution (>300). Between 51 and 100, the air quality is considered

moderate, a level where the population would be considered to not be affected, except for a reduced number of people. For an AQI in the interval of 101-200, the air quality is considered unhealthy, and at least one of the national standards for criteria pollutants had been exceeded. The other steps, 201-300 and > 300, represent a severe risk to public health.

The Brazilian air quality standards (AQS) are shown in Table 1. For comparison, the current air quality limits of the United States, European Union and World Health Organization Air Quality Guidelines (WHO AQG) are also shown.

Table 1 shows that the air quality standards in the EU are somewhat more restrictive than in Brazil and the US. The WHO established guidelines for SO<sub>2</sub>, NO<sub>2</sub>, PM<sub>10</sub>, particulate matter < 2.5 mm (PM<sub>2.5</sub>) and O<sub>3</sub>.<sup>12</sup> All these pollutants are monitored in the US and the EU. In Brazil, PM<sub>2.5</sub> is not a criteria pollutant. Following the recommendations of the WHO, some monitoring stations have been provided with PM<sub>2.5</sub> samplers, but the levels are not reported or considered for the calculations of the AQI. In addition, the EU monitors a larger number of compounds that are set out in the WHO recommendations (CO, benzene, lead and benzo(a)pyrene). The US also monitors CO and lead.

In the US, the Clean Air Act (NAAQS),<sup>10</sup> and in Brazil, the CONAMA Resolution,<sup>8</sup> established two types of national air quality standards. Primary standards set limits to protect public health, including the health of "sensitive" populations (e.g., children, asthmatics), while secondary standards set limits to protect the public welfare (e.g., damage to animals, plants and buildings). These standards are focused primarily on assessing the level of pollution that would be an acceptable level of risk to public health. The European Union, on the other hand, has established air quality limits at levels at which the probability of the impact of pollution on human health is minimal or none. In addition, the EU, in the process of setting air quality limits, was guided by the WHO guidelines.

In this work, the AQIs determined in Rio de Janeiro from July to September 2016 in the monitoring stations operated by the SMAC are compiled. The concentrations of the main criteria pollutants are discussed in terms of the Brazilian, US, EU and WHO guidelines.

## Experimental

### Monitoring sites

Rio de Janeiro is the second largest city in Brazil. It is on the South Atlantic coast, near coordinates 22°54'S and 43°12'W. The Tijuca Forest, which is a mountainous

**Table 1.** Comparison of current air quality limits in the Brazilian, EU, US and WHO guidelines

Pollutant	Average time	Brazil (CONAMA) <sup>8</sup>	US (NAAQS) <sup>10</sup>	EU (AQS) <sup>11</sup>	WHO <sup>12</sup>
SO <sub>2</sub> / ppb	1 h mean	—	75	134	—
	3 h mean	—	500	—	—
	24 h mean	53	140	48	8
	annual mean	15	30	—	—
NO <sub>2</sub> / ppb	1 h mean	—	100	106	106
	24 h mean	101	—	—	—
	annual mean	53	53	21	21
PM <sub>10</sub> / (µg m <sup>-3</sup> )	24 h mean	150	150	50	50
	annual mean	50	—	40	20
PM <sub>2.5</sub> / (µg m <sup>-3</sup> )	24 h mean	—	35	—	25
	annual mean	—	15	25	10
CO / ppm	8 h mean	9	9	10	—
	1 h mean	35	35	—	—
Ozone / ppb	8 h mean	80	70	60	50
	1 h mean	—	—	—	—
Benzene / (µg m <sup>-3</sup> )	1 year	—	—	5	—
Lead / (µg m <sup>-3</sup> )	1 year	—	0.15	0.5	—
PAH / (µg m <sup>-3</sup> ) (expressed as benzo(a)pyrene)	1 year	—	—	0.001	—

US NAAQS: United States National Air Quality Standards; EU AQS: European Union Air Quality Standards; WHO: World Health Organization; PM<sub>10</sub>: particulate matter < 10 mm; PM<sub>2.5</sub>: particulate matter < 2.5 mm; PAH: polycyclic aromatic hydrocarbon.

rainforest area, forms a natural barrier to air circulation and divides the city into northern and southern sections. Some of the more upscale neighborhoods and many of the major tourist sites, such as the Rodrigo de Freitas Lagoon and Sugar Loaf and Corcovado Mountains, as well as the famous beaches of Copacabana, Leblon and Ipanema, are located in the South Zone. The Maracanã Stadium and Quinta da Boa Vista Park are located in the North Zone. The West Zone is a rapidly growing suburban area including the districts of Barra da Tijuca and Deodoro, where most of the Olympic arenas were constructed.

According to the Köppen climate classification scheme,<sup>15</sup> the climatic condition of Rio de Janeiro is Group A (Tropical megathermal) Atlantic tropical (Aw). The average annual temperature varies between 23 and 24 °C, where the highest monthly average occurs during the summer in February (28.7 °C) and the lowest monthly average occurs during the winter in July (21.3 °C). The annual relative humidity average varies between 70 and 80%, with no significant variation during the year. The total accumulated annual rainfall is approximately 1,200 mm, generally representing a rainy season (from October to March) and a dry season (from April to September). Air circulation in the metropolitan area is significantly affected by topographical conditions.<sup>15</sup>

The automatic monitoring stations installed and operated by the State Agency, INEA, were located in the four Olympic zones: Recreio and Jacarepaguá (Barra);

Gericinó and Campo dos Afonsos (Deodoro); Lagoa, Leblon and Urca (Copacabana); and Maracanã, Engenho de Dentro and Centro (Maracanã). They determined the daily concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> and the hourly concentrations of ozone.<sup>7</sup> The obtained data were collated as the calculated AQI, and only the pollutant that represented the worst conditions was reported.<sup>5</sup>

The Municipal Agency, SMAC, operated eight fixed stations: Copacabana, Tijuca (approximately 2 km from Maracanã Stadium), Centro, São Cristóvão, Pedra de Guaratiba, Irajá, Bangú and Campo Grande.<sup>6</sup> Data were reported to the population as a daily bulletin with the AQI and the maximum concentration of each determined pollutant. However, only four stations (Tijuca, Bangú, Irajá and Campo Grande) determined all the criteria pollutants during the Olympic and Paralympic Games. CO, SO<sub>2</sub>, O<sub>3</sub> and NO<sub>2</sub> concentrations were obtained at intervals of 10 min and PM<sub>10</sub> in 1 h intervals.<sup>16</sup> The locations of the monitoring stations are shown in the Supplementary Information section, Figure S1, as well as the Olympic zones in Maracanã, Barra, Copacabana and Deodoro. The data obtained in these monitoring stations are discussed in this work. Wind roses calculated for the period July–September 2016, with data provided by the four monitoring stations are presented in the Supplementary Information section (Figure S2), with locations, as well as the temperature and solar radiation profiles (Figures S3 and S4).

## Bangu

Bangu District is situated in the geographic center of the city. It is approximately 20 km away from the Atlantic coast and is surrounded by Gericino (970 m) and Pedra Branca (1,020 m) mountains, which are natural barriers for the circulation of air. The district has an area of 45.07 km<sup>2</sup> and a population of 243,000 inhabitants.<sup>17</sup> Considering the area in the proximity of the monitoring stations (a radius of 2 km), the population is approximately 413,000. The air quality monitoring station is installed in the central area of the district (22°53'16.53"S and 43°28'15.91"W). The predominant winds are from the west and west-southwest.<sup>6</sup> The mean temperatures in July, August and September, for the period 1961-1990, were 20.5, 21.8 and 22.5 °C, respectively.<sup>18</sup> The district is considered to be the Rio de Janeiro area with the highest temperatures, and it is characterized by frequent ozone episodes. In the July 2014-July 2016 period, the national air quality standard was exceeded 185 times, considering the ozone hourly measurements.<sup>19</sup>

## Campo Grande

The monitoring station is located (22°53'10.25"S and 43°33'24.12"W) in Maina Square, an urban area in the proximity of Paciência (altitude 202 m) and Inhoáiba (altitude 245 m) hills. Campo Grande has an area of 120 km<sup>2</sup> and a population of approximately 358,000 with important industrial (plastic, metallurgical, food, pharmaceutical, chemical products), commercial and rural activity.<sup>6</sup> The predominant winds are from the northeast and southeast due to the influence of the marine breeze.

## Irajá

The station is located in Nossa Senhora da Apresentação Square (22°49'53.71"S and 43°19'36.71"W), a commercial area near the Irajá Cemetery. The square contains leisure and open walking areas and hosts cultural events. Considering the area in the proximity of the monitoring station (a radius of 2 km), the population is approximately 461,000.<sup>6</sup> Weak maritime breezes from the east-southeast are predominant, with a contribution from mountain breezes from the southwest.<sup>6</sup>

## Tijuca

The station is located at Saens Peña Square (22°55'30.07"S and 43°13'57.33"W), a central area in the Tijuca District in the northern part of the city of Rio

de Janeiro, approximately 10 km from the entrance of Tijuca National Park and approximately 1 km from the mountainous rainforest area. The district has an area of 1,006.56 km<sup>2</sup> and a population of 165,000 inhabitants.<sup>17,20</sup> Considering the area in the proximity of the monitoring station (a radius of 2 km), the population is approximately 461,000 and comprises the Districts of Tijuca, Maracanã, Rio Comprido, São Cristóvão, Vila Isabel, Andaraí and Alto da Boa Vista. The Maracanã Stadium is approximately 2 km from the square and can be accessed by subway, buses and car. Approximately 60% of its area is urbanized, and 30% is covered by Mata Atlântica (tropical rainforest) species. The studied area is characterized by commercial activities and a high flux of vehicles and people because of a terminal subway station as well as many restaurants, bars and leisure activities. Due to the proximity of the Tijuca Forest mountains, maritime breezes do not reach this area. Weak mountain breezes from the south and southwest are the most frequent, and the region is poorly ventilated.<sup>6</sup>

## Data processing

Daily AQI reports were compiled and analyzed to determine the pollutants of major concern. Then, the concentrations (10 min mean) were displayed in the form of box-plot diagrams using code in the R language (version 3.3.1)<sup>21</sup> to compare the four sampling locations and the three-month period. Box-plots diagrams characterize the samples using the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentiles, also known as the lower quartile (Q1), median (Q2) and upper quartile (Q3). In this study, the box length is the interquartile range (IQR = Q3 - Q1) and the median value is indicated as a black line inside the box. Whiskers are extended to the most extreme data point that is no more than 1.5 × IQR from the edge of the box and outliers are indicated as circles.

## Results and Discussion

Daily AQIs were determined in July-September 2016 in the automatic stations, Tijuca (Saens Peña), Bangu, Campo Grande and Irajá. AQIs were calculated at 3:00 PM for the previous 24 h.<sup>16</sup> The AQIs were calculated using the Brazilian 5-level classification: good (< 50), moderate (51-100), unhealthy (101-200), very unhealthy (201-300) and hazardous (> 300), as shown in Table 2.<sup>14</sup> The detailed calculation of the AQI is detailed by SMAC and also presented in Supplementary Information section (Table S1 and equation S1).<sup>22</sup> These AQIs are similar to the 6-level scale adopted in the US: good, moderate, unhealthy to sensitive groups, unhealthy, very unhealthy and hazardous.<sup>23</sup>

The calculated values are shown in Figure 1. The worst air quality conditions were observed in Bangu and Irajá. In Irajá, the ozone concentration value of  $201 \text{ mg m}^{-3}$  was exceeded on two days (August 16 and September 18), leading to an AQI  $> 200$ . In Bangu, the ozone air quality standard ( $160 \text{ mg m}^{-3}$ ) was exceeded on 4, 2 and 3 days in July, August and September, respectively, leading to an AQI  $> 100$ . In Irajá, the AQI was  $> 100$ , due to ozone concentrations, on 3 and 4 days in July and August, respectively. For the studied period, on 15.0, 31.5, 33.7 and 61.9% of the days at the four stations, the AQI was  $< 50$  (good air quality).

Moreover, despite the governmental policies to reduce pollutant emissions during the Olympic and Paralympic Games, the concentrations of ozone, nitrogen oxides and  $\text{PM}_{10}$  were near or above the levels of concern. In view of these AQI values, a detailed analysis of concentration data was performed.

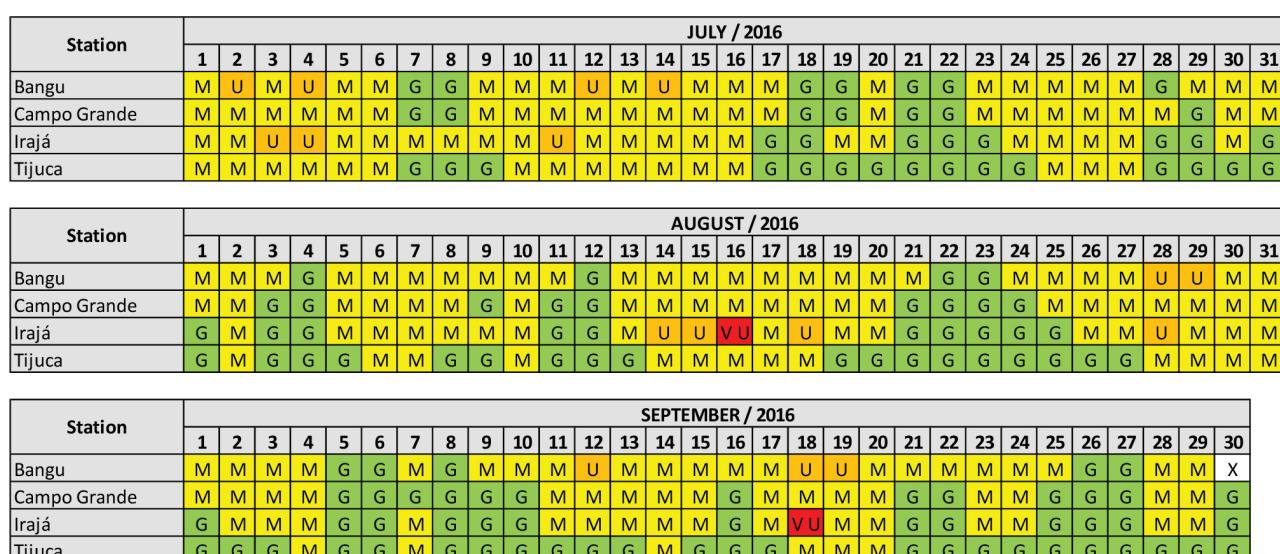
Ozone concentration profiles as a function of the hour of the day are shown in Figures 2-5. The values of 80, 160 and  $200 \text{ mg m}^{-3}$  are also shown. As previously

mentioned, 1 h mean values of  $81\text{-}161 \text{ mg m}^{-3}$  leads to a moderate AQI (51-100), 1 h mean values of  $161\text{-}200 \text{ mg m}^{-3}$  leads to an unhealthy AQI (101-200), 1 h mean values of  $201\text{-}800 \text{ mg m}^{-3}$  leads to a very unhealthy AQI (201-300).

An inspection of Figure 2 shows that the value of  $200 \text{ mg m}^{-3}$  was exceeded in July and September, but since the period was  $< 60 \text{ min}$ , the classification of the AQI was moderate. However, in these conditions, the most sensitive individuals and the athletes might experience serious health effects. The WHO AQG<sup>12</sup> for ozone was reduced in 2005 to  $100 \text{ mg m}^{-3}$  (daily maximum 8 h mean). According to the WHO,<sup>12</sup> as ozone concentrations increase above this value, health effects became increasingly numerous and more severe. At  $160 \text{ mg m}^{-3}$  (daily maximum 8 h mean), there is evidence of changes in lung function and lung inflammation in healthy young adults undertaking intermittent exercise.<sup>12</sup> Values determined in Bangu were below the WHO AQG in the studied period, but considering that July-August correspond to the winter season in the Southern Hemisphere and the flux of people and vehicles was lower due to the Olympic Games, higher concentrations

**Table 2.** Air quality indexes (AQIs) adopted in Brazil and their health implications<sup>14</sup>

AQI	Air pollution level													Health implications												
0-50	good													air quality is considered satisfactory, and air pollution poses little or no risk for the population												
51-100	moderate													air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution												
101-200	unhealthy													everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects												
201-300	very unhealthy													health warnings of emergency conditions. the entire population is more likely to be affected												
> 300	hazardous													health alert: everyone may experience more serious health effects, there is risk of premature deaths												

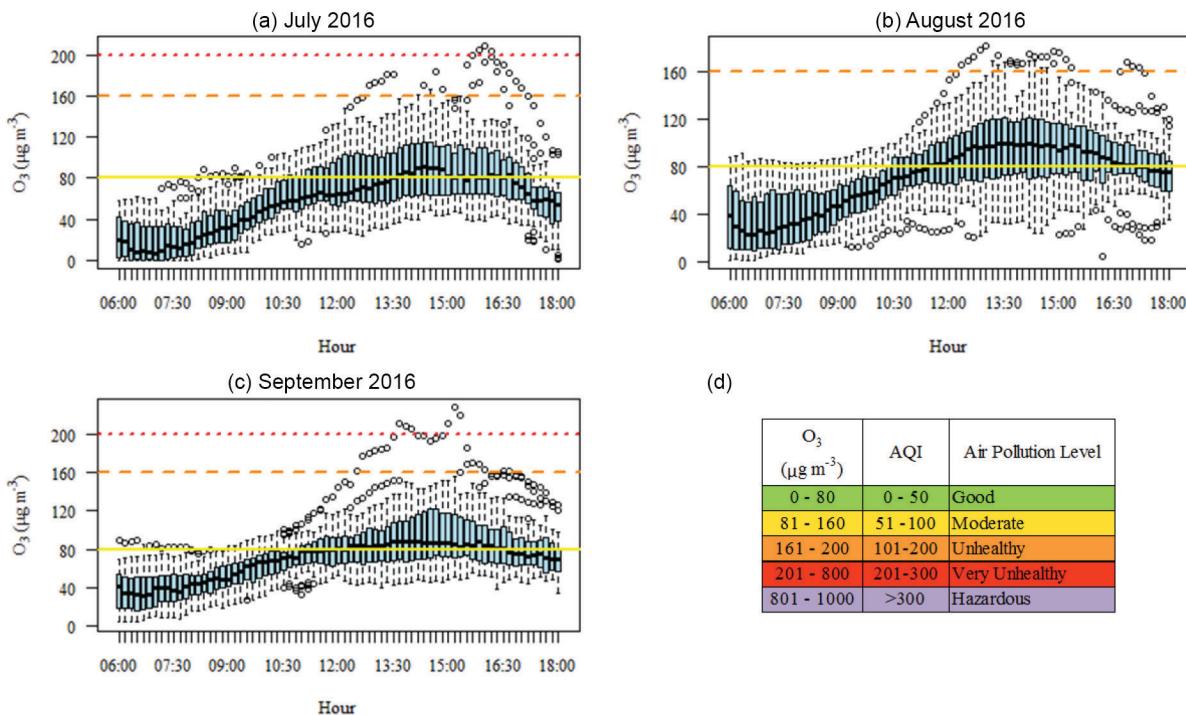


**Figure 1.** AQIs determined in July-September 2016 in the automatic monitoring stations: Bangu, Campo Grande, Irajá and Tijuca.

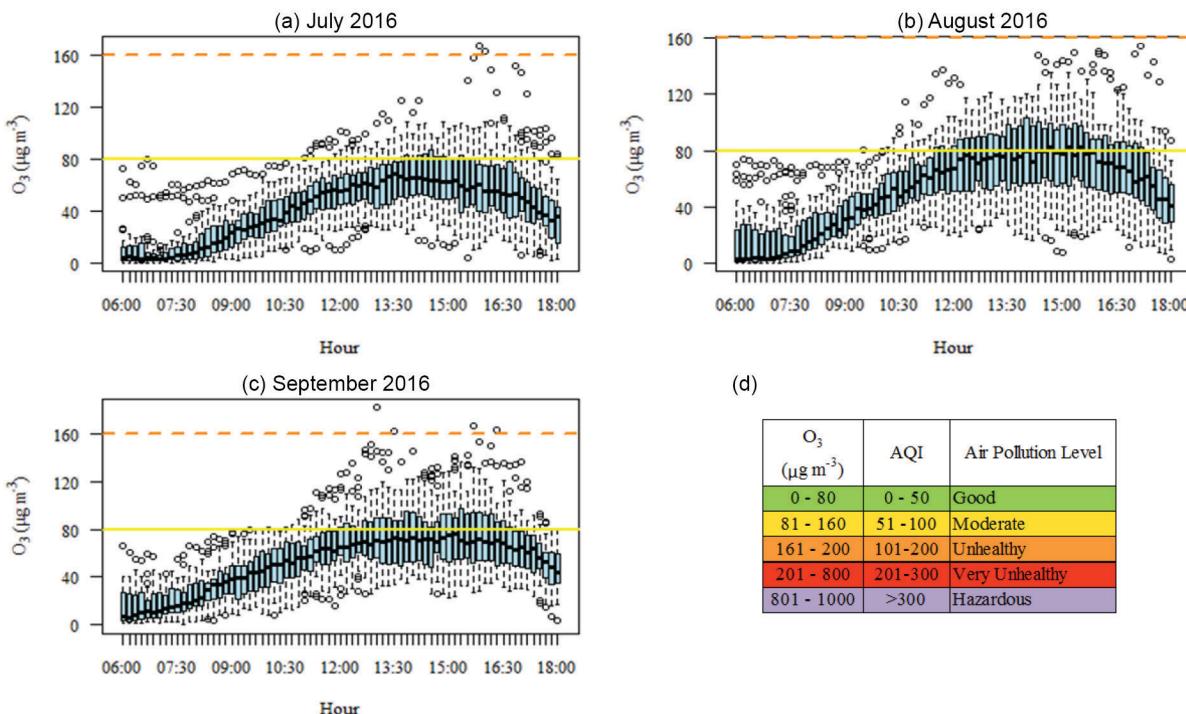
would be expected in current summer days, increasing the population exposure.

Similar results were obtained for Irajá (Figure 4). In August and September,  $200 \text{ mg m}^{-3}$  was exceeded for a period  $> 60 \text{ min}$ , leading to an unhealthy AQI classification, as

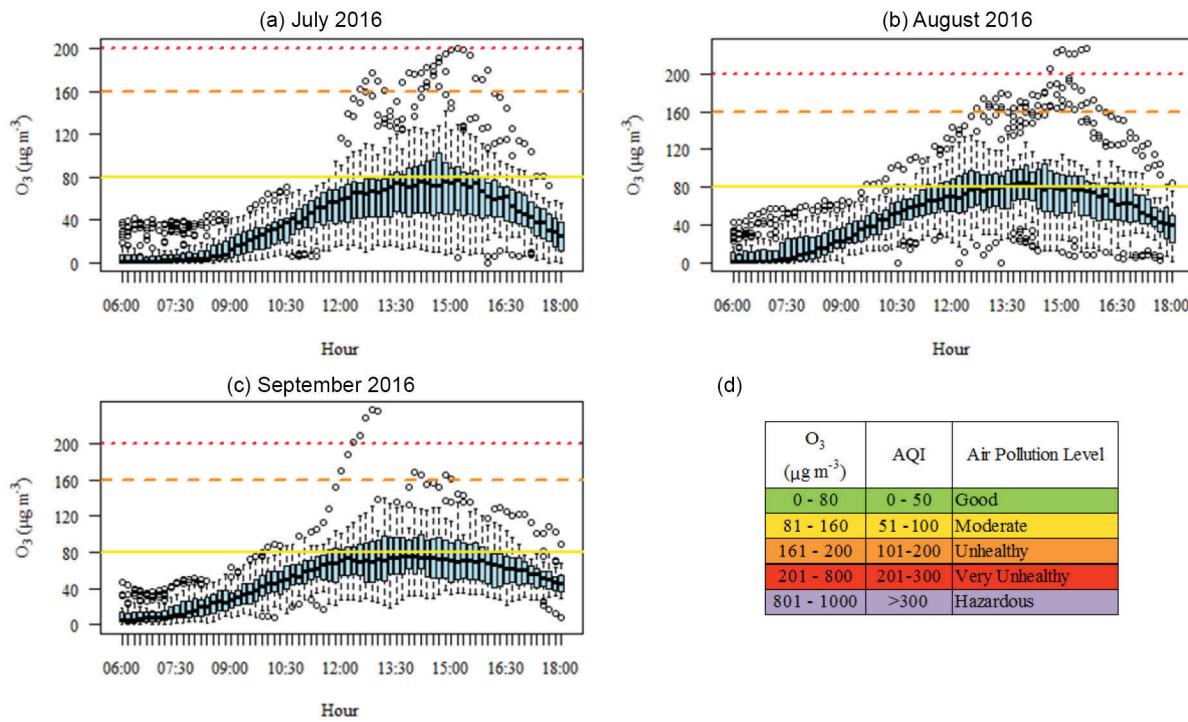
previously shown in Figure 1. For Campo Grande and Tijuca, values were in general below  $160 \text{ mg m}^{-3}$  (1 h mean). Values in August and September were higher than those obtained in July, due to the temperature and solar radiation being generally approximately 10-15% lower in July, as determined



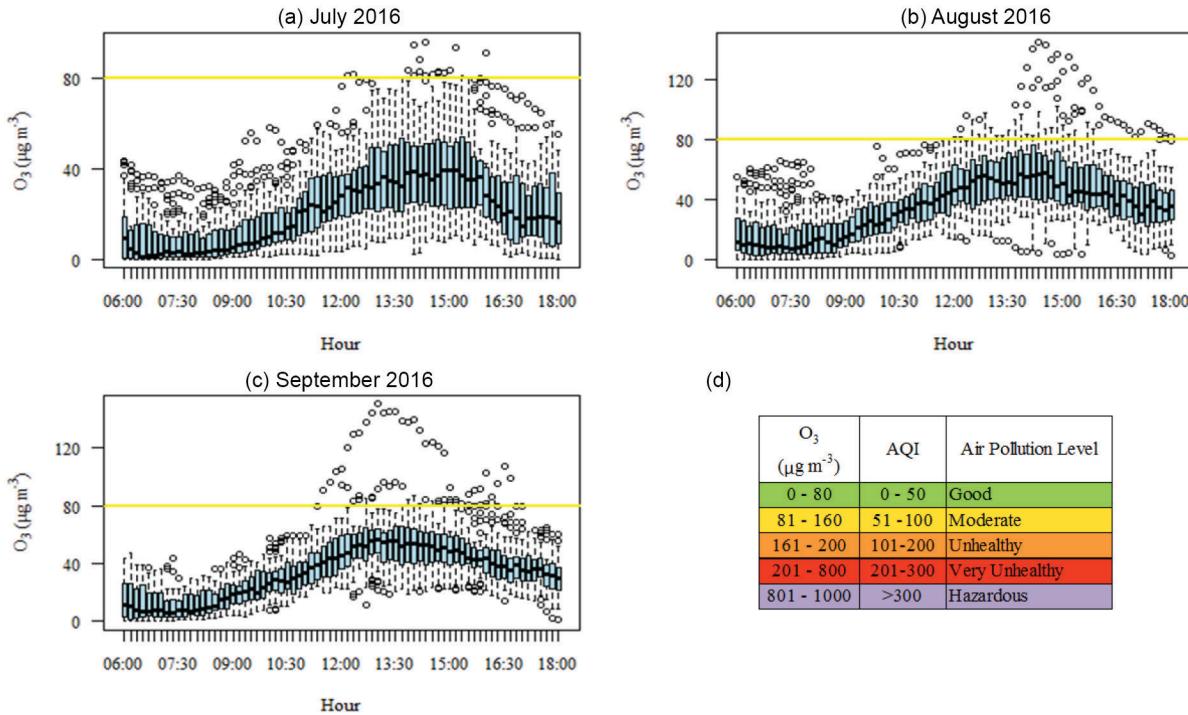
**Figure 2.** Ozone concentration profiles as a function of the hour of the day for Bangu. (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.



**Figure 3.** Ozone concentration profiles as a function of the hour of the day for Campo Grande. (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.



**Figure 4.** Ozone concentration profiles as a function of the hour of the day for Irajá. (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.



**Figure 5.** Ozone concentration profiles as a function of the hour of the day for Tijuca. (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.

in the monitoring stations. Temperature and solar radiation data obtained in Irajá and Bangú, respectively, are shown in the Supplementary Information section (Figures S3 and S4).

$\text{NO}_2$  1 h means were, in general, lower than  $100 \text{ mg m}^{-3}$  in Bangú, Campo Grande and Irajá. The  $\text{NO}_2$  concentration

profiles as a function of the hour of the day are shown in the Supplementary Information section (Figures S5-S7). The values determined in Tijuca are presented in Figure 6. The box-plots show that approximately 75% of the data points are lower than  $100 \text{ mg m}^{-3}$ . However, values  $> 100 \text{ mg m}^{-3}$

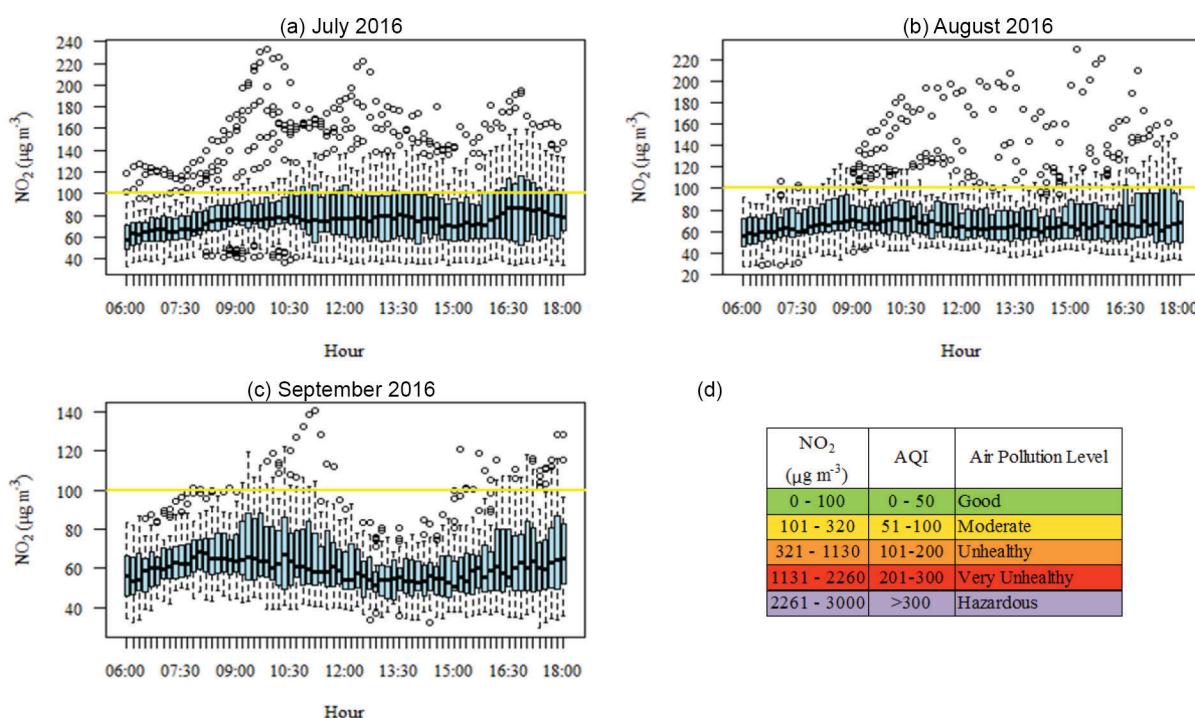
are frequently observed. During the Olympic Games (August 5-21), this value was exceeded on 8 days (47% of the days), with a maximum value of  $209 \text{ mg m}^{-3}$  on August 16. Historical data for Tijuca show that  $\text{NO}_2$  concentrations in the interval of  $100\text{-}320 \text{ mg m}^{-3}$  are frequent, due to the high vehicular flux, mainly of diesel-fueled buses.

It is worth noting the inverse correlation between  $\text{NO}_x$  (where  $\text{NO}_x = \text{NO} + \text{NO}_2$ ) and  $\text{O}_3$  in Rio de Janeiro urban area.<sup>19,24</sup> The reaction of  $\text{O}^{(\text{P})}$  with  $\text{O}_2$  is the only known anthropogenic source of tropospheric ozone.<sup>25</sup>  $\text{O}_3$  is formed through a complex chemical process involving volatile organic compounds (VOCs) and  $\text{NO}_x$ .<sup>26</sup> In this process, the hydroxyl radical ( $\bullet\text{OH}$ ) is the key reactive species which reacts with anthropogenic and biogenic VOCs, forming intermediate  $\bullet\text{RO}_2$  and  $\bullet\text{HO}_2$  radicals. These radicals react with NO and convert it to  $\text{NO}_2$ , which subsequently decomposes and photochemically forms  $\text{O}^{(\text{P})} + \text{NO}$ . Ozone may also react with VOCs, forming intermediate radicals, and NO, forming  $\text{NO}_2 + \text{O}_2$ . Therefore, the net photochemical formation of  $\text{O}_3$  versus net photochemical loss of  $\text{O}_3$  in the troposphere depends on the NO concentration and reactivity of the VOC mixture.<sup>25</sup> Simulated and experimental results show that in Rio de Janeiro urban area VOCs/ $\text{NO}_x$  ratios are, in general  $< 8$ . In this conditions the kinetic process is VOCs-limited and an increase in NO concentrations results in lower  $\text{O}_3$  concentrations. This seemingly contradictory behavior is due to the  $\text{O}_3 + \text{NO}$  reaction and also to the scavenging of

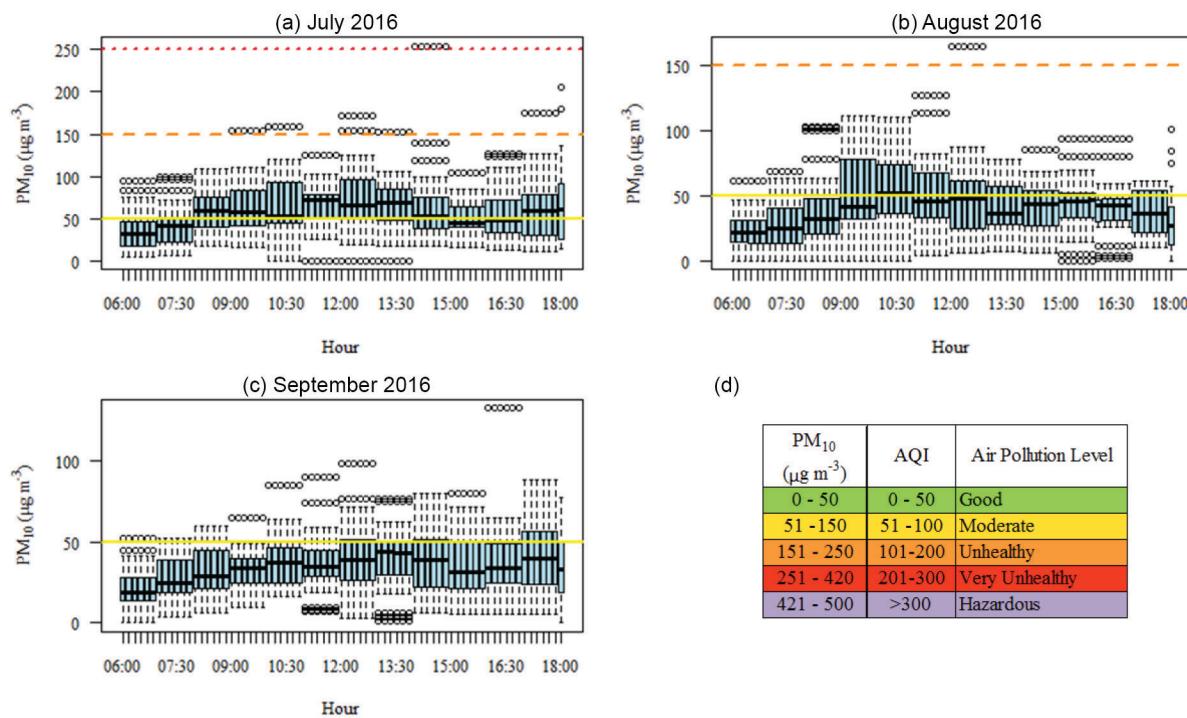
the radicals which propagate the VOCs oxidations and the  $\text{NO}$ -to- $\text{NO}_2$  conversion. The  $\text{NO}_2$  competes with VOCs for the hydroxyl radicals slowing intermediate  $\bullet\text{RO}_2$  and  $\bullet\text{HO}_2$  radicals production.<sup>26</sup> This inverse correlation was observed in the monitoring stations. For example, in Tijuca, the higher  $\text{NO}_2$  (Figure 6) and lower  $\text{O}_3$  concentrations (Figure 5) were observed in July.

For  $\text{PM}_{10}$ , the 24 h national standard is  $150 \text{ mg m}^{-3}$  in Brazil<sup>8</sup> and US<sup>10</sup> and  $50 \text{ mg m}^{-3}$  in the EU.<sup>11</sup> The WHO AQG is also  $50 \text{ mg m}^{-3}$ .<sup>12</sup> The annual means are  $50$  and  $20 \text{ mg m}^{-3}$  for Brazil and WHO, respectively. Values determined in the period July-September 2016 in Bangu, Campo Grande, Irajá and Tijuca are shown in Figures 7-10. Values are reported by SMAC as 1 h means.

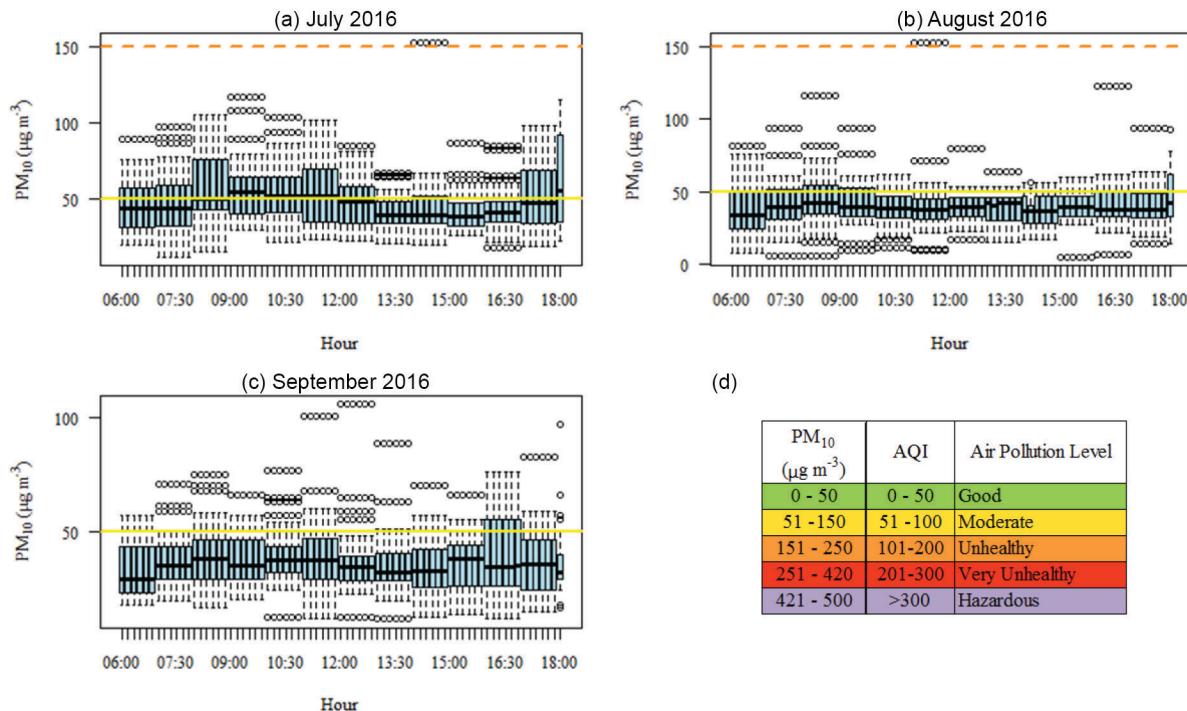
In July 2016, 1 h medians were in general higher than  $50 \text{ mg m}^{-3}$  in Bangu and Irajá. Additionally, more than 50% of the individual values for the four locations were higher than  $20 \text{ mg m}^{-3}$ , the WHO AQG for the annual average concentration. This value was established considering the lower end of the range over which significant effects on survival were observed in the American Cancer Society's study<sup>27</sup> and a  $\text{PM}_{2.5}/\text{PM}_{10}$  average ratio of  $0.5$ .<sup>12</sup> Higher primary pollutant concentrations in Irajá and Bangu can also be explained considering the wind roses for the studied period (Supplementary Information section, Figure S2) and the location of the monitoring stations. During that period, the districts received air masses from the east, impacted by the industrial area of Duque de Caxias, and the west,



**Figure 6.**  $\text{NO}_2$  concentration profiles as a function of the hour of the day for Tijuca (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.



**Figure 7.**  $\text{PM}_{10}$  concentration profiles as a function of the hour of the day for Bangu (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.

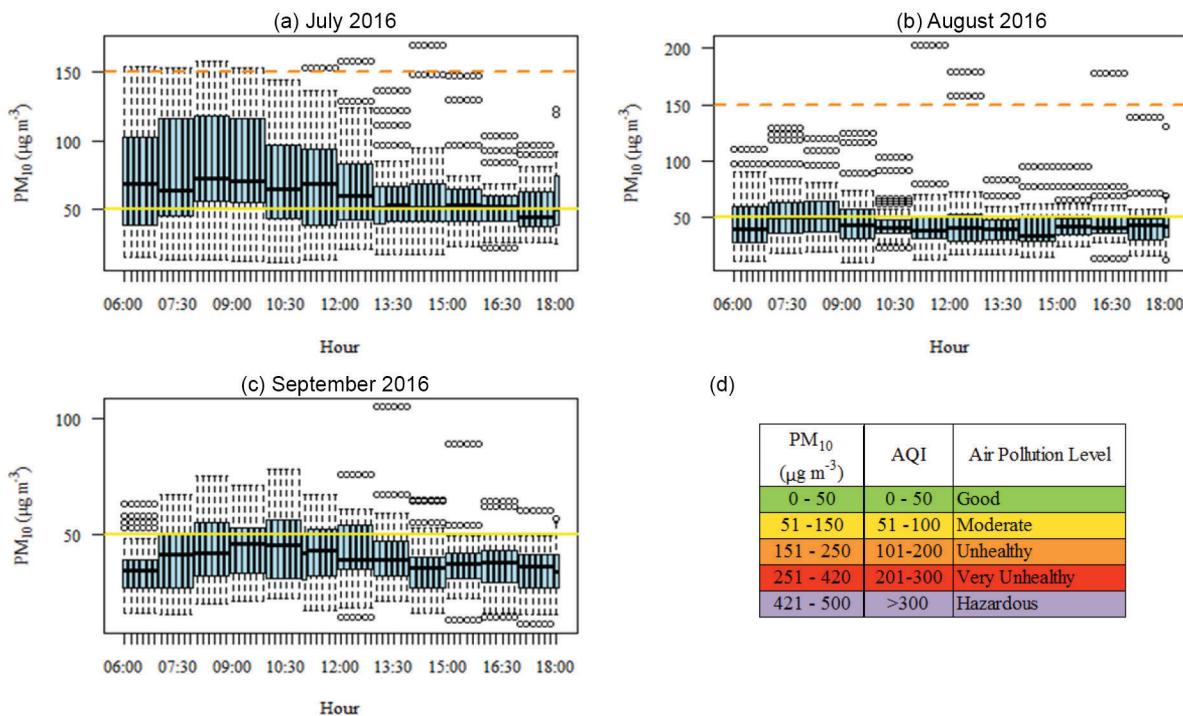


**Figure 8.**  $\text{PM}_{10}$  concentration profiles as a function of the hour of the day for Campo Grande (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.

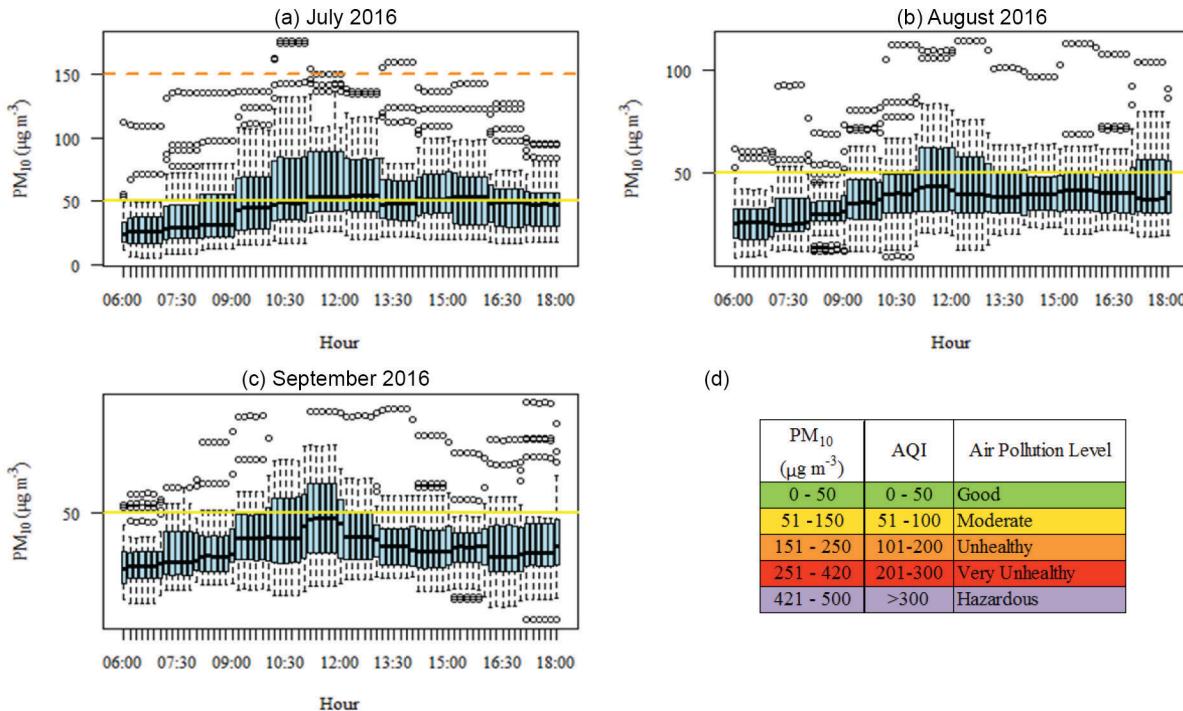
impacted by the industrial area of Santa Cruz.

Annual  $\text{PM}_{10}$  concentration mean values were reported by SMAC<sup>6</sup> for 2011 and 2012 in the four locations. Hourly annual means were between 25 and 50  $\text{mg m}^{-3}$ , with lower values at night. Daily values were higher in winter due to

lower rainfall during July and August, with an accumulated rainfall < 100 mm.<sup>6</sup> In the period 2013-2015, annual means at the Olympic stations located in Deodoro, Maracanã and Leblon were in the interval 21-61  $\text{mg m}^{-3}$ , with the higher values in the Maracanã Stadium area.<sup>7</sup>



**Figure 9.** PM<sub>10</sub> concentration profiles as a function of the hour of the day for Irajá (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.



**Figure 10.** PM<sub>10</sub> concentration profiles as a function of the hour of the day for Tijuca (a) July 2016; (b) August 2016; (c) September 2016; (d) AQIs.

Clearly, 24 h values were lower than the Brazilian national standard ( $150 \text{ mg m}^{-3}$ ) in the pre-Olympic period (2013-2015) and during the Olympic Games, and the annual means are lower than the standard ( $50 \text{ mg m}^{-3}$ ) in most of the stations. A similar result was obtained for ozone, since

the national standard ( $160 \text{ mg m}^{-3}$ ) was not exceeded on most of the days. Considering the national standards and the Brazilian AQI, during the Olympic Games, the air quality was reported by INEA for the Olympic stations and by SMAC for seven stations.

Data reported by INEA for 2013-2015 showed that Deodoro and Maracanã were the Olympic areas of major concern in relation to air quality.<sup>5</sup> For example, in August 2015, the AQIs, calculated using ozone concentrations, in Campo dos Afonsos (Deodoro) and Maracanã were moderate on 63 and 32% of the reported days, respectively, indicating that ozone concentrations were in the interval 81-160 mg m<sup>-3</sup>, and on one day (August 31), the national air quality standard (160 mg m<sup>-3</sup>) was exceeded. The high ozone concentrations in Campo dos Afonsos were related to the proximity of Brazil Avenue, which is considered the main source of vehicular pollutants in Rio de Janeiro.<sup>7</sup> In August 2016, INEA reported that in Campo dos Afonsos and Maracanã stations, there were only one and two days, respectively, when the value of 80 mg m<sup>-3</sup> was exceeded.<sup>5</sup> The lower ozone levels could be attributed to the traffic restrictions in Brazil Avenue and other important circulation routes in the west and north area of the city and in the proximity of Maracanã Stadium.

The primary pollutants NO<sub>x</sub> and PM<sub>10</sub> were, in general, lower during the Olympic and Paralympic Games, mainly during the morning, probably due to the restrictions in vehicular flux and the holiday period in schools and universities. However, no reduction in ozone levels was observed. Previous results obtained in Bangu<sup>19</sup> in July 2016 showed that ozone levels depend dramatically upon solar radiation and temperature, which were higher in August and September than in July 2016.<sup>6</sup> A close analysis of Figures 2-5 shows that on several days, ozone concentrations in the early morning were relatively high (> 40 mg m<sup>-3</sup>), clearly showing the transport of aged masses of air or the poor dilution of air masses during night. During Rio 2016, the highest ozone concentrations were reported in Bangu and Irajá. These regions are characterized by higher temperatures and poor air circulation in comparison to the southern and western regions of the city and receive emissions from the industrial areas of Duque de Caxias (east), and Campo Grande and Santa Cruz (west). The combined result of restrictions to the circulation of vehicles, high values for national air quality standards<sup>28</sup> and the use of a limited number of compounds for the calculation resulted in AQIs that, in general, were in the interval 0-50 (good). However, ozone and PM<sub>10</sub> concentrations were frequently high in comparison to the WHO guidelines, representing a risk to the health of the population and the athletes.

The results obtained in Rio de Janeiro may be compared to those determined in other Olympic cities, especially Beijing, where many studies were published before and after the Olympic Games.<sup>29-39</sup> Several studies have been published on the results of surface and satellite

measurements during the Beijing Olympics (2008), indicating sharp decreases in the concentration of primary measured pollutants during the Olympic Games.<sup>36,39</sup> During the 2008 Olympic Games, the mean PM<sub>10</sub> concentration was 82.4 mg m<sup>-3</sup> at Peking University (PKU) in northwestern Beijing. The mean value reported by the Beijing Environmental Protection Bureau (EPB) was 53.7 mg m<sup>-3</sup>.<sup>32</sup> Daily concentrations reported by Wang *et al.*<sup>32</sup> showed that 12% of days exceeded the 24 h period and China's Ambient Air Quality Standard (CAAQS, grade II 150 µg m<sup>-3</sup>) and that 81% of days exceeded the WHO 24 h PM<sub>10</sub> QG (50 µg m<sup>-3</sup>) and CAAQS Grade I (50 µg m<sup>-3</sup>). However, considering the Beijing average, according to EPB, the CAAQS Grade II was not exceeded, and 44% of days exceeded the WHO AQG and CAAQS Grade I. When comparing these data with those obtained in Rio de Janeiro, it may be noted that while the decrease in PM<sub>10</sub> concentrations was moderate (< 15%) in Rio de Janeiro and restricted to the proximity of Olympic arenas, in Beijing, the mean PM<sub>10</sub> concentrations were reduced by 35% during the Olympic period compared to the non-Olympic period.<sup>32</sup>

However, as reported by Wang *et al.*,<sup>34</sup> levels of ozone, sulfate and nitrate in PM<sub>2.5</sub> increased during the Beijing Olympic Games by 16, 64 and 37%, respectively, compared to the period prior to the full emission control. The authors reported hourly ozone values up to 370 mg m<sup>-3</sup> and attributed the ozone episodes to the transport of chemically processed air masses from the North China Plain.

Air quality during the Olympic Games and other multi-sports events has been the subject of discussions at both scientific and governmental levels. Hosting the Olympic Games offers many benefits and opportunities to the candidate city. Many years of planning and investments are required to host a successful Olympic Games and to ensure that the Games leave a positive, long-term and sustainable legacy. This legacy includes an improvement in air quality and public health, not only during the Games, but also after the event. It also includes informing the public about the risk of air pollution, monitoring all the criteria pollutants and adopting long-term strategies to ensure a positive impact after the Games.

Recently, Chen *et al.*<sup>40</sup> analyzed the officially reported air pollution indexes in Beijing from 2000 to 2009 and showed that the adopted measures to improve the air quality during the Olympic Games improved the indexes during and briefly after the Games, but a significant proportion of the effect had faded by October 2009.

The subject has also been discussed before and after the London Olympic Games<sup>41-43</sup> and the Rio de Janeiro Olympic Games.<sup>44</sup>

Results discussed in this work show the importance of

using all the criteria pollutants when calculating the AQIs, since the use of a restricted number of compounds may lead to artificially low index values.

## Conclusions

Reported data showed that NO<sub>2</sub> and PM<sub>10</sub> concentrations were in general lower than 100 and 50 mg m<sup>-3</sup> (corresponding to a good AIQ), during the Olympic period because of the restrictions in vehicular flux. However, ozone concentrations remained high, exceeding the value 160 mg m<sup>-3</sup> (1 h mean), mainly in Bangu and Irajá, probably due to unfavorable meteorological conditions (relatively high temperatures and solar radiation and low wind speed) as well as high NO<sub>x</sub>/VOCs ratios.

Brazilian air quality allowable standards are clearly high in comparison to WHO guidelines, and the combined results of adopted air quality indexes and the use of a restricted number of criteria pollutants to report the air quality lead to AQIs in the intervals 0-50 (good) and 50-100 (moderate) despite concentrations being frequently high in terms of WHO guidelines.

The adoption of WHO AQG by the IOC during the Olympic candidature process and the election of the host city and the calculation of AQIs using all the criteria pollutants should be recommended.

## Supplementary Information

Supplementary data (map of the city, wind roses for the period July-August 2016, temperature values determined in Irajá, solar radiation values determined in Bangu, NO<sub>2</sub> concentration profiles as a function of the hour of the day for Bangu, Campo Grande and Irajá, concentrations intervals for the calculation of the air quality indexes) are available free of charge at <http://jbcs.sbj.org.br> as PDF file.

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