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URBAN AIR QUALITY, CLIMATE AND POLLUTION: FROM MEASUREMENT TO MODELING APPLICATIONS

# Avoiding hospital admissions for respiratory system diseases by complying to the final Brazilian air quality standard: an estimate for Brazilian southeast capitals

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**Abstract**
According to the World Health Organization (WHO), in 2016, 91% of the global population was living in places where guidelines on air quality were not met, which results in an estimated figure of seven million deaths annually. The new Brazilian air quality standards, CONAMA 491/2018, was the first revision in over two decades and has as final target the WHO guidelines for air quality, although no deadline has been established for implementation. The goal of this work was to quantify public health gains of this new policy based on hospitalizations due to respiratory diseases, the most studied outcome in Brazilian time series studies, in four Brazilian Southeast capitals: São Paulo (SP), Rio de Janeiro (RJ), Belo Horizonte (MG), and Vitória (ES) for $PM_{10}$, $PM_{2.5}$, $SO_2$, CO, and $O_3$. Population and hospitalizations data for all respiratory diseases for people under 5 years old, over 64 years old, most vulnerable populations, and all ages were analyzed. The air quality monitoring data was analyzed in two different periods: 2016 to 2018 for São Paulo and Vitória; and between 2015 and 2017 for Belo Horizonte and Rio de Janeiro, according to available monitoring data. A literature review was carried out to determine the appropriate relative risk to be used in the estimations, and the public health gains were calculated based on the selected relative risks for each city. The highest estimate was for São Paulo, with 3454 avoidable respiratory hospital admissions (all ages). In total, the four cities accounted for 4148 avoidable hospitalizations, which was associated to $1.1 million public health gains. Results considering the day of exposure (lag 0) were superior to those with the 5-day moving average (lag 5). The results highlighted the importance of adopting more restrictive standards and called for public policies, the necessity of expanding the air quality monitoring network, mapping emission sources, and improve the knowledge about the interaction between air pollution and health outcomes beyond respiratory disease for the region.

**Keywords** Health benefits · Excess hospitalizations · Diseases of the respiratory system · Relative risks · Economic gains · Brazil

## Introduction

The rapid urbanization process has increased the amount of mobile and stationary pollution sources. In Brazil, urban population reached 86.6% of the total in 2018 (United Nations 2015; The World Bank 2019) and they are exposed to progressively higher levels of atmospheric pollution (Salvi and Barnes 2009; Andrade et al. 2017; Pacheco et al. 2017). In 2016, 91% of the global population was living in places where the World Health Organization (WHO) guidelines on air quality were not met, which results in an estimated figure of seven million deaths annually (35% stroke; 30% ischemic heart disease; 17% chronic obstructive pulmonary disease; 9% lower

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respiratory infections; and 9% lung cancer) (WHO 2018). Andreão et al. (2018) showed that 90% of the annual concentrations of fine particulate matter ($PM_{2.5}$) in Brazilian cities that monitor this pollutant were higher than the annual WHO guideline (10 μg $m^{-3}$).

Atmospheric pollutants, such as total suspended particles (TSP), smoke, inhalable particles ($PM_{10}$ and $PM_{2.5}$), sulfur dioxide ($SO_2$), carbon monoxide (CO), ozone ($O_3$), and nitrogen dioxide ($NO_2$) are associated with varying levels of penetration in the respiratory system, reaching as far as the bloodstream (Arbex et al. 2012). Cohort studies already found evidence of $PM_{2.5}$ being statistically associated to mortality of all causes, cardiopulmonary, and lung cancer (Pope III et al. 2019). The effects of these pollutants on human health are more acutely observed in children, elderly and people who have diseases due to a weak immune system (Gouveia and Fletcher 2000a, 2000b; Bakonyi et al. 2004; Castro et al. 2009; Gonçalves et al. 2012; Nascimento et al. 2017). Such circumstances emphasize the need to improve air quality in urban environments.

To promote atmospheric pollution reduction policies, an understanding of current ambient air local context is necessary, usually achieved through air quality monitoring and health assessment techniques. According to the Brazilian air quality monitoring network diagnosis (IEMA 2014), only nine of the 26 Brazilian states and the Federal District have a monitoring network. Among Brazilian cities, merely 1.7% are covered by monitoring stations and 78% of these cities are in the Southeast region. This indicates that the coverage in Brazil is not only scarce but also concentrated on specific regions. Furthermore, there is a gap in monitored pollutants: monitoring of $PM_{2.5,}$ for example, only occurs in the Brazilian Southeast (Andreão et al. 2018).

The WHO guidelines on air quality were published for the first time in 1987 (WHO 1987) and the latest update refers to the year 2005 (WHO 2006). The revision process is based on scientific studies that relate the effect of pollution on human health. Other factors such as the opinion of air quality managers and implemented public policies are considered in the design and format of the guidelines, to enhance its applicability in several parts of the world. The pollutants of concern considered are: $PM_{10}$, $PM_{2.5}$, $SO_2$, $O_3$, and $NO_2$.

In Brazil, the air quality standards (AQS) were updated by the National Environment Council (CONAMA) with the CONAMA Resolution n° 491/2018, revised for the first time after more than two decades. The new Resolution establishes intermediary air quality standards (IS) to be progressively reached along the years aiming at a final standard (FS) based on WHO guidelines. This methodology has already been employed by the states of São Paulo and Espírito Santo, through states legislations (State Decree n° 59,113/2013 for São Paulo and State Decree n° 3463-R/2013 for Espírito Santo). The regulated pollutants are TSP, smoke, $PM_{10}$, $PM_{2.5}$, $SO_2$, CO, $O_3$, $NO_2$, and Pb, as showed in Table 1.

However, the new legislation has been subject of controversy due to the fact that the current standard (IS-1) and the two subsequent intermediate standards are still very permissive, when compared to WHO guidelines. Moreover, no deadlines were established for the implementation of each one of the phases. The absence of a clear future timeline does not contribute to expand monitoring across the country. Despite its limitations, the new legislation is an advance when compared to the previous standards, dated back to 1990.

In this context, the goal of this work is to estimate the number of hospital admissions that would have been avoided due to a decrease in atmospheric pollutant concentrations based on the final CONAMA Resolution n° 491/2018 standards. $PM_{10}$, $PM_{2.5}$, $SO_2$, CO, and $O_3$ were analyzed for the four Southeast state capitals: São Paulo, Rio de Janeiro, Belo Horizonte and Vitória. This work evaluated the effect on children (< 5 years old) and the elderly (> 64 years old) according to the epidemiological studies that supported the data used. The Southeast region capitals were selected due to its important role in Brazil's socioeconomic landscape, as it is responsible for 18% of Brazil's GDP (IBGE 2018), concentrating 10% of the Brazilian population.

The Southeast capitals are large urban centers with problems related to air pollution. The major Brazilian cities have a high degree of occupation in peripheral areas and dispersion of economic activities, which can result in long commutes for activities related to work, study or leisure (Lessa et al. 2019). In recent years, an increase in vehicle fleet was observed in Brazil, driven mainly by the reduction of purchasing taxes, but also due to an increase in income and credit in the population, especially for the first decade of the 2000s (Vasconcellos et al. 2011; Lessa et al. 2019). In Belo Horizonte, for example, population increased by 6.10% between 2000 and 2010, whereas the vehicle fleet grew up 97% (SISMOB-BH 2015). By encouraging the use of personal vehicles through tax exemptions and lack of policies that prioritize public transportation, there is a decrease in the quality and demand for public transport. This contributes to the rising number of personal vehicles, sometimes advertised as the only efficient mean of transportation, especially for those with higher incomes (Araújo et al., 2011).

On the other hand, positive changes were observed in the last decades. Strong public policies promoted an increase in the use of biofuels, such as ethanol and biodiesel (Pacheco et al. 2017). In 2014, the National Agency of Petrol, Natural Gas and Biofuels (ANP) reduced the sulfur content of gasoline from 800 to 50 mg $kg^{-1}$, and for diesel from 50 to 10 mg $kg^{-1}$, which resulted in a reduction of $SO_2$ emissions (Nogueira et al. 2015; Albuquerque et al. 2019). There was also an increase in the ethanol and biodiesel content in gasoline and diesel, respectively, which lead to a reduction in emission rates of particulate matter,

**Table 1** Air quality standards according to CONAMA Resolution 491/2018. IS stands for "intermediary standard" and FS for "final standard." The current AQS (2019) is the IS-1

| Atmospheric Pollutant | Reference period | IS-1 $\mu g\ m^{-3}$ | IS-2 $\mu g\ m^{-3}$ | IS-3 $\mu g\ m^{-3}$ | FS $\mu g\ m^{-3}$ |
|---|---|---|---|---|---|
| Particulate matter—$PM_{10}$ | Daily average | 120 | 100 | 75 | 50[a] |
| | Annual average | 40 | 35 | 30 | 20[a] |
| Particulate matter—$PM_{2.5}$ | Daily average | 60 | 50 | 37 | 25[a] |
| | Annual average | 20 | 17 | 15 | 10[a] |
| Sulfur dioxide—$SO_2$ | Daily average | 125 | 50 | 30 | 20[a] |
| | Annual average | 40 | 30 | 20 | – |
| Nitrogen dioxide—$NO_2$ | Hourly average | 260 | 240 | 220 | 200[a] |
| | Annual average | 60 | 50 | 45 | 40[a] |
| Ozone—$O_3$ | Maximum 8-h moving average in 1 day | 140 | 130 | 120 | 100 |
| Smoke | Daily average | 120 | 100 | 75 | 50 |
| | Annual average | 40 | 35 | 30 | 20 |
| Carbon monoxide—CO | Maximum 8-h moving average in 1 day | – | – | – | 9 ppm |
| Total suspended particles—TSP | Daily average | – | – | – | 240 |
| | Annual geometric average | – | – | – | 80 |
| Lead—Pb | Annual average | – | – | – | 0.5 |

[a] same values as the WHO Guidelines (WHO 2006)

$SO_2$ and greenhouse gasses, such as methane and carbon dioxide (Nogueira et al. 2014; Pacheco et al. 2017).

The cities in the Brazilian Southeast region present a tropical climate with wet (October to April) and dry (May to September) seasons, but each city has particularity that influence its pollutant dispersion and climatic conditions. São Paulo is the largest city in Brazil and one of the biggest in the world, with a population of more than 12 million inhabitants (IBGE 2019a), and its climate is influenced by the large urbanization, the traffic fleet of over 7 million vehicles as well as phenomena such as heat islands and sea breeze (Freitas et al. 2007; Rodriguez et al. 2010; Miranda et al., 2012; Pacheco et al. 2017). As a result of the large number of vehicles, the Environmental Company of the state of São Paulo identified that the air quality problems in Metropolitan Area of São Paulo are mainly linked to ozone and particulate matter, suggesting a reduction of 20.5% in NOx and VOC and 4.8% in PM.

Rio de Janeiro is the second largest city in Brazil, with a population estimated of 6.8 million inhabitants (IBGE 2019b). The large variety of economic activities result in several sources of air pollution, from transportation sector to industries such as petrochemical, naval, chemical, food and energy transformation. The complex topography, irregular land use, and the Guanabara Bay are factors that can contribute to an irregular dispersion of pollutants in the city (Onursal and Gautam 1997; Soluri et al. 2007; Pacheco et al. 2017).

Belo Horizonte, capital of Minas Gerais state, has a population of 2.5 million (IBGE 2019c), and a vehicle fleet of over two million vehicles, which are the most representative source of air pollution in the city (Santos 2018; Santos et al. 2019). The landscape in Belo Horizonte went through changes in the last decades, one being the verticalization of the neighborhoods in its southern area, near the hills that surround the city (mountainous topography), that may have altered local pollutant dispersion conditions (Cortizo 2002; Vilela 2007; Pacheco et al. 2017).

Lastly, Vitória, capital of Espírito Santo and one of the largest cities in its state, with an estimated population of 360,000 inhabitants (IBGE, 2019d), has a history with air pollution due to the significant industrial activity in its metropolitan area, especially from steel industry as well as pelletizing and coking plants, to which the large majority of air pollutants in the area can be attributed, together with vehicle sources (IEMA 2019; Galvão et al. 2019). Dust suspension from traffic was identified as the main source of particulate matter according to the local environmental agency (IEMA 2019; Freitas et al. 2016). São Paulo and Rio de Janeiro have extensive air quality monitoring networks, with 17 and 30 stations respectively, whereas Belo Horizonte (2 stations) and Vitória (3 stations) have a smaller coverage.

In this work, the short-term public health effect of air pollution is assessed in terms of hospital admissions due to respiratory diseases, the most studied outcome in Brazilian epidemiological time series studies. Gouveia et al. (2017) studying the largest Brazilian metropolis (metropolitan area of São Paulo - MASP) concluded that cardiovascular diseases were statistically relevant in fewer cities than respiratory diseases, which may be linked to age range, covariables, and the statistic technique regarding the regression. As cardiovascular disease is relevant in cities with air pollution, more studies are necessary to investigate their relationship with air pollutants. Gouveia et al. (2019) showed that respiratory diseases were the outcome most related to $PM_{10}$, $SO_2$, and CO in Belo Horizonte.

Aiming to estimate the public health gains from reducing atmospheric pollutant concentration, a literature review was carried out to select the appropriate relative risks for $PM_{10}$, $PM_{2.5}$, $SO_2$, $O_3$, and CO for each city, encompassing children, the elderly, and all ages.

## Literature review on relative risks

A relative risk (RR) is a percentual risk factor derived from an adverse health effect and a cause. When the RR is above 1.00, it means an increase in risk (or a negative health effect), and when it is below, it indicates a positive effect (a protective effect). In terms of air pollution, the risk of suffering from a health effect is usually related to an increase in the ambient concentration of a specific pollutant, called an increment.

Searches on online database were conducted (in English and Portuguese), using Scopus, Periódicos Capes portal (a Brazilian virtual library which include Web of Science), and Google Scholar, with combinations of the following key words and their acronyms: morbidity, hospital admission, hospitalization, health impact, epidemiological study, air pollution, air quality, hazard ratio, relative risk, besides the specific pollutants.

Thirty-six scientific articles were found and analyzed for 36 cities since 1999. Only seven of the studies calculated RR for cities outside the Southeast region. Freitas et al. (2013) and Bakonyi et al. (2004) studied the city of Curitiba (South region), Agudelo-Castañeda et al. (2019) studied five cities in the Metropolitan Area of Porto Alegre (South Region), while Carmo et al. (2010), Ignotti et al. (2010), Machin and Nascimento (2018) and Silva et al. (2013) focused on cities in the state of Mato Grosso, in the Central-west region, which is more acutely affected by the atmospheric pollution emitted by fires in the Amazon Forest and Cerrado (a tropical savanna ecoregion of Brazil). Overall, São Paulo was the most studied city (ten studies), followed by other cities in the same state, such as Cubatão and São José dos Campos, which are industrial cities in the outskirts of the Metropolitan Area of São Paulo, 60 km and 100 km distant from the capital, respectively. The cities of Vitória and Rio de Janeiro, also in the Southeast region, were the subject of four and three studies, respectively. Because of the limited number of cities and pollutants studied by the epidemiological researches in Brazil, there is a lack of information concerning specific pollutants in other locations, including some of the cities analyzed in this study.

Regarding the four Southeast capitals, two studies representing Belo Horizonte RR for $PM_{10}$ were observed: Freitas et al. 2013 presented a RR of 1.06% (CI 0.41%–1.72%) for all ages and 1.25% (CI 0.25%–2.26%) for children under 5 years old, while Gouveia et al. (2019) found negative percent RR for lag-0 and lag-5 in children up to 5 years old. For Rio de Janeiro, a study calculated RR for $O_3$, considering the hospital admissions regarding pneumonia only (Moura et al. 2009). Table 2 shows the RR found for $PM_{10}$, along with its confidence interval (CI). For other pollutants, a complete table is presented in the supplementary information (S1).

Among all pollutants, $PM_{10}$ was the focus of most epidemiological studies. The higher relative risk was found for Itabira city, in the state of Minas Gerais, as equal to 12% (95% CI 9.5%–14.5) (Braga et al. 2007). According to the authors, the mining activity in the city increases the particulate matter emissions, which would have affected the local population health. São Paulo also presented high RRs 13.78% (CI 4.21%–23.35%) for $O_3$ (Martins et al. 2002); 11.30% (CI 5.9%–16.80%) for CO (Braga et al. 1999); 18.00% (CI 4.14%–31.85%) for $SO_2$ (Martins et al. 2002) and 18.4% (CI 12.5%–24.3%) for $NO_2$ (Farhat et al. 2005). A lack of information concerning $PM_{2.5}$ was observed: only 11 studies (31%) analyzed this pollutant, and most of them were due to economic activities in the cities in question, such as sugar cane burning (Cançado et al. 2006; César et al. 2013) or due to specificities of the Amazon region, such as forest burning and deforestation (Machin and Nascimento, 2018; Ignotti et al. 2010; Carmo et al. 2010). Excepted for Ignotti et al. (2010), which focused on respiratory diseases in the subequatorial Amazon for the elderly, studies concerning $PM_{2.5}$ concentrated in the age group below 13 years old.

Regarding age groups, articles focused on groups previously identified as most susceptible to air pollution. The effect on children was the most studied, as 29 of the articles presented RR for children under 15 years old. $PM_{10}$ and $O_3$ were the pollutants most investigated for this group, in 25 and 18 articles, respectively. A RR calculated for the elderly were presented in nine studies, and the highest RR recorded for this group were 18.4% (CI 12.5%–24.3%) for $NO_2$ (Farhat et al. 2005) and 17.90% (CI 12.6%–23.5%) for $SO_2$ (Gouveia et al. 2006), both in São Paulo. The RR from hospital admissions in all ages was also analyzed in eight studies.

Fewer Brazilian epidemiological studies investigated the relationship between air pollutants and cardiovascular diseases. Besides respiratory diseases, Ferreira et al. (2016) also investigated circulatory diseases, with the RR percentage being smaller for $PM_{10}$ in elderly for this outcome, 2.7% (CI −2.2%–7.9%), against 12.8% (CI 6.0–20.0) for respiratory diseases. Considering $PM_{10}$, Freitas et al. (2013) obtained different relationship between RR for total respiratory diseases and cardiovascular diseases (over 39 years old) for different cities. In Belo Horizonte for example, the RR was double for cardiovascular than for respiratory (1.06 and 2.29, respectively). Otherwise, for São Paulo city the RR was significant just for respiratory diseases (1.11). Freitas et al. (2016) obtained higher RR in Vitória for respiratory than cardiovascular

**Table 2** Literature review on relative risks for $PM_{10}$

| Reference | City | Period studied | Increment ($\mu g\ m^{-3}$) | Age group | Disease studied | Relative risk (95% CI) | Lag |
|---|---|---|---|---|---|---|---|
| Braga et al. (1999) | São Paulo (SP) | 10/1992–10/1993 | Not informed | < 13 | All respiratory diseases | 1.11 (1.04–1.19) | Lags until 7 |
| Gouveia and Fletcher (2000b) | São Paulo (SP) | 11/1992–09/1994 | 98.1 | < 5 | All respiratory diseases | 1.040 (0.985–1.099) | Lag 0 |
| Gouveia et al. (2006) | São Paulo (SP) | 05/1996–04/2000 | 10 | < 5 | All respiratory diseases | 1.024 (1.017–1.031) | The most statistically relevant results were lag 5 |
| | | | | < 5 | Asthma | 1.046 (1.033–1.060) | |
| | | | | < 5 | Pneumonia | 1.021 (1.014–1.029) | |
| | | | | > 64 | All respiratory diseases | 1.022 (1.014–1.031) | |
| | | | | > 64 | Chronic obstructive pulmonary disease | 1.043 (1.028–1.058) | |
| | | | | > 64 | Pneumonia | 1.019 (1.007–1.030) | |
| Gouveia et al. (2017) | São Paulo (SP) | 2000–2008 | 10 | < 5 | All respiratory diseases | 1.011 (1.009–1.013) | Lags until 5 |
| | | | | all ages | | 1.017 (1.015–1.019) | |
| | Diadema (SP) | | | < 5 | | 1.012 (1.005–1.020) | |
| | | | | All ages | | 1.012 (1.007–1.017) | |
| | Guarulhos (SP) | | | < 5 | | 1.010 (1.002–1.017) | |
| | | | | All ages | | 1.017 (1.012–1.021) | |
| | Mauá (SP) | | | < 5 | | 1.077 (1.056–1.098) | |
| | | | | All ages | | 1.021 (1.008–1.033) | |
| | Osasco (SP) | | | < 5 | | 1.012 (1.007–1.017) | |
| | | | | All ages | | 1.012 (1.008–1.015) | |
| | São Bernardo do Campo (SP) | | | < 5 | | 1.033 (1.019–1.046) | |
| | | | | All ages | | 1.032 (1.024–1.040) | |
| | São Caetano do Sul (SP) | | | All ages | | 1.015 (1.006–1.024) | |
| | Santo André (SP) | | | < 5 | | 1.009 (1.001–1.017) | |
| | | | | All ages | | 0.997 (0.992–1.002) | |
| | Taboão da Serra (SP) | | | < 5 | | 1.015 (0.997–1.034) | |
| | | | | All ages | | 1.014 (1.003–1.026) | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | São Paulo (SP) | 01/1993–11/1997 | 35 | < 2 | All respiratory diseases | 1.094 (1.079–1.109) | Lag 7 |
| | | | | 3–5 | | 1.033 (1.002–1.063) | |
| | | | | 6–13 | | 1.019(0.988–1.050) | |
| | | | | 14–19 | | 1.051 (1.003–1.098) | |
| | | | | < 19 | | 1.070 (1.057–1.082) | |
| Freitas et al. (2004) | São Paulo (SP) | 01/1993–12/1997 | 71.8 | < 15 | All respiratory diseases | 1.1004 (1.0775–1.1238) | Lag 1 |
| Gouveia et al. (2003) | São Paulo (SP) | 1996–2000 | 10 | < 5 | All respiratory diseases | 1.067 (1.049–1.086) | Lags until 5 |
| | | | | > 65 | | 1.019 (1.011–1.027) | |
| | Rio de Janeiro (RJ) | 2000–2001 | 10 | < 5 | All respiratory diseases | 1.018 (1.004–1.033) | |
| | | | | > 65 | | 1.035 (1.012–1.059) | |
| Moura et al. (2009) | Rio de Janeiro (RJ) | 04/2002–03/2003 | 10 | < 2 | Pneumonia | 1.0510 (0.992–1.1136) | Lag 5 |
| | | | | 6–12 | | 1.0468 (0.9577–1.1441) | |
| | | | | < 12 | | 1.0145 (0.9736–1.0543) | |
| Freitas et al. (2016) | Metropolitan area of Vitória (ES) | 2001–2006 | 10 | All ages | All respiratory diseases | 1.0967 (1.0764–1.11) | Lag 5 |
| | | | | < 5 | | 1.0660 (1.0375–1.0953) | |
| | | | | | | 1.056 (1.006–1.11) | Lag 6 |
| Gouveia et al. (2019) | Belo Horizonte (MG) | 2001–2006 | 10 | < 5 | All respiratory diseases | 0.998 (0.982–10,141) | Lag 0 |
| | | | | | | 0.9984 (0.985–10,120) | Lag 5 |
| | Betim (MG) | | | | | 1.0045 (1.059–1.0254) | Lag 0 |
| | | | | | | 1.007 (0.9924–1.0292) | Lag 5 |
| | Contagem (MG) | | | | | 1.013 (0.9988–1.0343) | Lag 0 |
| | | | | | | 0.999 (0.9808–1.0192) | Lag 5 |
| Souza et al. (2018) | Metropolitan area of Vitória (ES) | 01/2005–12/2010 | 10.49 | < 7 | All respiratory diseases | 1.02 (1.010–1.039) | |
| Nardocci et al. (2013) | Cubatão (SP) | 2000–2008 | 10 | All ages | All respiratory diseases | 1.0425 (1.0282–1.0571) | Lags until 5 |

**Table 2** (continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | < 5 | | 1.0574 (1.0380–1.0771) | |
| Jasinski et al. (2011) | Cubatão (SP) | 1997–2004 | 56.5 | < 5 | All respiratory diseases | 1.096 (1.03–1.161) | Lags 2 to 4 |
| Ferreira et al. (2016) | São José dos Campos (SP) | 03/2010–02/2011 | 10 | All ages | All respiratory diseases | 1.128 (1.060–1.200) | Lags until 5 |
| Nascimento et al. (2006) | São José dos Campos (SP) | 05/2000–12/2001 | 24.7 | < 10 | Pneumonia | 1.098 | Lag 7 |
| Souza and Nascimento (2016) | Araraquara (SP) | 01/2010–11/2012 | 10 | < 10 | Pneumonia | 1.15 | Lag 0 |
| Negrisoli and Nascimento (2013) | Sorocaba (SP) | 01/2007–12/2008 | 10 | < 10 | Pneumonia | 1.009 (1.002–1.016) | Lag 4 |
| Cançado et al. (2006) | Piracicaba (SP) | 04/1997–03/1998 | 10.2 | < 13 | All respiratory diseases | 1.3103 (1.0125–1.6081) | |
| Bakonyi et al. (2004) | Curitiba (PR) | 01/1999–12/2000 | 90.39 | < 15 | All respiratory diseases | 1.0008 (1.0004–1.0012) | Lag 0 |
| Braga et al. (2007) | Itabira (MG) | 01/2003–01/2004 | 10 | < 13 | All respiratory diseases | 1.04 (1.022–1.058) | Lag 2 |
| | | | | 14–19 | | 1.12 (1.095–1.145) | Lag 3 |
| Carmo et al. (2010) | Alta Floresta (MT) | 01/2004–12/2005 | 10 | < 5 | All respiratory diseases | 1.029 (1.003–1.055) | Lag 6 |
| | | | | | | 1.026 (1.000–1.054) | Lag 7 |
| Agudelo-Castañeda et al. (2019) | Canoas (RS); Charqueadas (RS); Esteio (RS); Gravataí (RS) and Trunfo (RS) | 2013–2016 | 10 | 1 5 | respiratory infections; asthma; chronic obstructive pulmonary disease | 1.0163 (1.0151–1.0179) | Monthly-term |
| | | | | > 60 | | 1.0108 (1.0107–1.0111) | |
| Freitas et al. (2013) | Belo Horizonte (MG) | 2000–2008 | 10 | All ages | All respiratory diseases | 1.006 (1.0041–1.0172) | Lags until 5 |
| | Betim (MG) | | | | | 1.0133 (1.0048–1.0218) | |
| | Contagem (MG) | | | | | 1.0123 (1.0032–1.0215) | |
| | Rio de Janeiro (RJ) | | | | | 1.0081 (1.0046–1.0116) | |
| | Duque de Caxias (RJ) | | | | | 1.0016 (0.995–1.0083) | |
| | Curitiba (PR) | | | | | 1.0284 (1.0237–1.0330) | |
| | Vitória (ES) | | | | | 1.0967 (1.0754–1.1184) | |
| | Campinas (SP) | | | | | 1.0215 (1.0155–1.0276) | |
| | Cubatão (SP) | | | | | 1.0378 (1.0233–1.0525) | |
| | Paulínia (SP) | | | | | 1.0376 (1.0146–1.0612) | |
| | São José dos Campos (SP) | | | | | 1.0261 (1.0191–1.0332) | |
| | Osasco (SP) | | | | | 1.0118 (1.0081–1.0155) | |
| | Diadema (SP) | | | | | 1.0116 (1.0065–1.0167) | |
| | Guarulhos (SP) | | | | | 1.0167 (1.0120–1.0214) | |
| | São Paulo (SP) | | | | | 1.0111 (1.0099–1.0123) | |
| | Taboão da Serra (SP) | | | | | 1.0142 (1.0031–1.0256) | |
| | São Bernardo do Campo (SP) | | | | | 1.0320 (1.0241–1.0400) | |
| | São Caetano do Sul (SP) | | | | | 1.0148 (1.0060–1.0236) | |

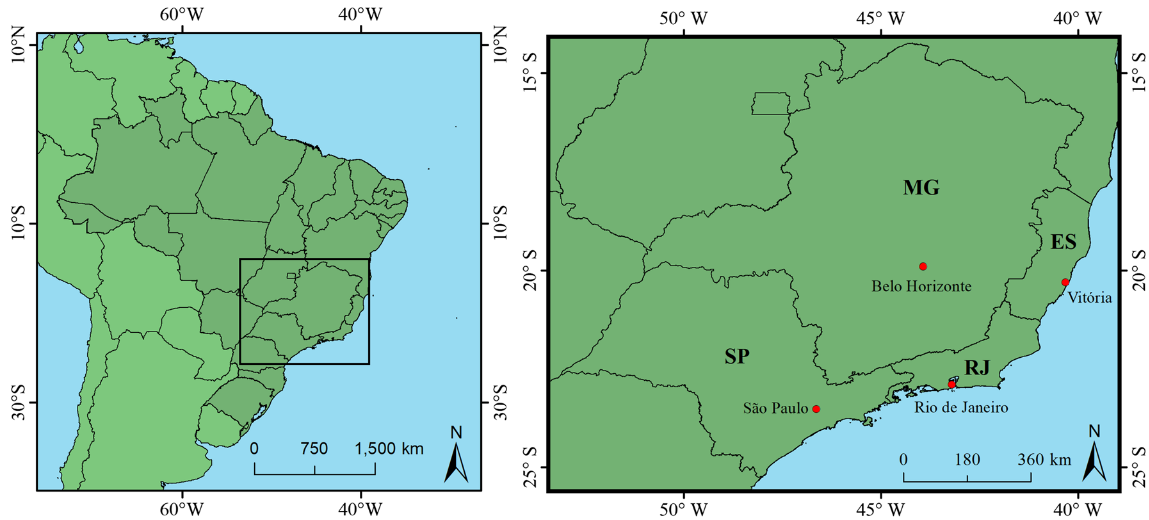



**Fig. 1** Brazilian Southeast Capitals for the states of São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ) and Espírito Santo (ES)

diseases for $PM_{10}$ and $SO_2$. Gouveia et al. (2019) showed RR (5-days moving average) higher for cardiovascular (over 39 years old) for $PM_{10}$ and $SO_2$ in Belo Horizonte, and smaller for CO, compared to respiratory diseases. In this context, cardiovascular diseases were not investigated in the present study because the scarcity number of epidemiological studies regarding this outcome for the four cities, which not support a reliable analysis of the benefits related to an improvement in air quality for this outcome.

## Methodology

The analysis of public health benefits due to the air pollution reduction considered the four state capitals in the Southeast of Brazil: São Paulo (São Paulo state) Rio de Janeiro (Rio de Janeiro state), Vitória (Espírito Santo state) and Belo Horizonte (Minas Gerais state), according to Fig. 1.

To estimate avoided hospital admissions, the log-normal concentration-response function (Eq. 1) was used, based on Sacks et al. (2018).

$$\Delta Y = Yo*Pop*\left(1-e^{\beta*\Delta C}\right)$$

where $\Delta Y$ is the estimated health impact attributed to air pollution, $\beta$ is the coefficient estimated by Eq. 2, $\Delta C$ is the difference between baseline and control scenarios, $Yo$ is the baseline rate (i.e., incidence rate of respiratory diseases) for hospital admissions due to respiratory diseases, and $Pop$ is the population exposed to air pollution (Sacks et al. 2018).

$$\beta = RR/\Delta Q$$

where $\Delta Q$ is the change in pollutant concentration used for the $RR$ estimation in the epidemiological studies.

The information used to perform the analysis and its sources is presented in Table 3. Population and hospital admissions data were obtained from the Health Services Information Database (DATASUS) of the Brazilian Unified Health System (SUS) (DATASUS 2019). Data on population is presented in.

Table 4 and the hospital admissions for the study groups are presented in Fig. 2. Daily incidence rate was calculated assuming an equal distribution in days from the available monthly data. Hourly air quality monitoring data was obtained from the environmental agencies of the

**Table 3** Period and sources of the data used in the analysis

| Dataset | Information | Period | Source |
|---|---|---|---|
| Hospital admissions | Monthly hospital admissions due to respiratory diseases (ICD-10: J00-J99) in elderly people (> 64 years old) and children (< 5 years old) and for the total population | 2016–2018 (São Paulo and Vitória) 2015–2017 (Belo Horizonte and Rio de Janeiro) | DATASUS (2019) |
| Population | Total population and population of elderly people (> 64 years old) and children (< 5 years old) | 2015 | DATASUS (2019) |
| Air quality monitoring data | Hourly $PM_{10}$, $PM_{2.5}$, $SO_2$, $O_3$, and CO concentration | 2016–2018 (São Paulo and Vitória 2015–2017 (Belo Horizonte and Rio de Janeiro) | CETESB, INEA, IEMA and FEAM |

**Table 4** Population data for the year of 2015 (DATASUS 2019). The numbers in brackets indicate the percentage related to the total population

| City | Total population | < 5 years old | > 64 years old |
|---|---|---|---|
| São Paulo | 11,967,824 | 739,684 (6%) | 1,096,987 (9%) |
| Rio de Janeiro | 6,476,629 | 380,663 (6%) | 749,222 (12%) |
| Belo Horizonte | 2,502,554 | 141,427 (6%) | 243,583 (10%) |
| Vitória | 355,876 | 22,870 (6%) | 32,299 (9%) |

states of São Paulo (CETESB), Rio de Janeiro (INEA), Espírito Santo (IEMA) and Minas Gerais (FEAM). Each pollutant concentrations for each city was calculated considering the average of all measurements performed within the area of each city. Daily concentrations were calculated in conformity with new final Brazilian air quality standard, which are 24-h averages for $PM_{10}$, $PM_{2.5}$, and $SO_2$ and a maximum concentration of 8-h moving average obtained in 24 h (MDA8) for $O_3$ and CO. As CO concentration levels were found to be in conformity with the legislation in all cities investigated, no avoided hospital admissions were estimated for this pollutant.

Aiming to better represent the environmental characteristics of each city (geographic location, emission sources and pollutants mixtures) (Boldo et al. 2014; Andreão et al. 2018), different relative risks were chosen to represent each city, according to data available in the literature, time and location of epidemiological study, lag between exposure and hospital admission, and age group, as presented in Table 5. The priority in selecting relative risks to perform the analysis was as follows: (1) risks estimated in the same city (2) risks estimated in other Southeast region capitals, considering similarities in emission sources (3) risks estimated in other Southeast region cities.

The RR presented in Gouveia et al. (2006) was used in São Paulo and Belo Horizonte. Even though this work estimated risks specifically for São Paulo, it was also used in Belo Horizonte due to the lack of risk estimations for this city for the lags investigated. For Vitória, RRs from Freitas et al. (2016) and Souza et al. (2018) ($PM_{10}$, $SO_2$, and $O_3$) were used. For Rio de Janeiro, the RR from Gouveia et al. (2003) was used for $PM_{10}$ and $SO_2$. Due to unavailability of RR for $O_3$ in Rio de Janeiro, the risk presented in Gouveia et al. (2006) was used for this pollutant. The RR presented in Nascimento et al. (2017) for $PM_{2.5}$ was used in all cities due to the lack of information available regarding this pollutant for each city specifically. As it was explained in the literature review, an estimative for the elderly was not performed, since the only RR available for the elderly was calculated for the Amazon region and not directly related to urban pollution. The estimative of avoidable hospital admissions considered two approaches: pollutants daily means (lag-0) and 5-day moving average (lag-5). When the lag was specified in the

**Table 5** Relative risks used in the analysis

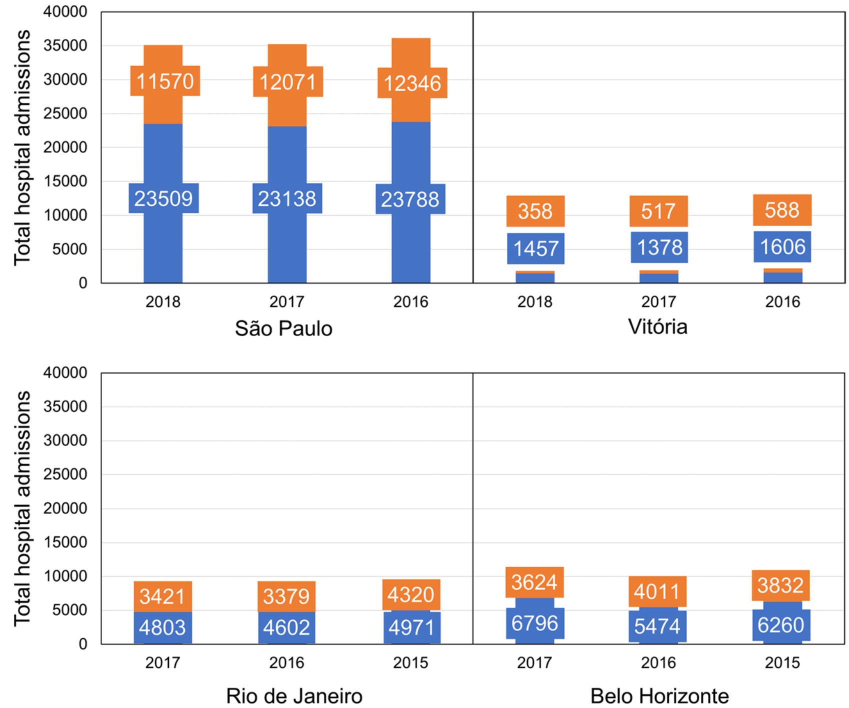
| Pollutant | Relative Risk | | Reference |
|---|---|---|---|
| | < 5 years old | > 65 years old | |
| São Paulo | | | |
| $PM_{10}$ | 1.024 | 1.022 | Gouveia et al. (2006) |
| $SO_2$ | 1.067 | 1.113 | |
| $O_3$ | 1.008 | 1.009 | |
| $PM_{2.5}$ | 1.0382 (lag 0) | – | Nascimento et al. (2017) |
| | 1.056 (lag 5) | – | |
| Vitória | | | |
| $PM_{10}$ | 1.0967 (lag 5) | 1.0152 (lag 0) | Freitas et al. (2016); |
| | 1.0027 (lag 0) | 1.066 (lag 5) | Souza et al. (2018) |
| $SO_2$ | 1.04 (lag 0)[1] | 1.0136 (lag 0) | |
| | 1.0698 (lag 5) | 1.0519 (lag 5) | |
| $O_3$ | 1.033 (lag 0) | – | |
| | 1.0193 (lag 5) | 1.0368 (lag 5) | |
| $PM_{2.5}$ | 1.0382 (lag 0) | – | Nascimento et al. (2017) |
| | 1.056 (lag 5) | – | |
| Rio de Janeiro | | | |
| $PM_{10}$ | 1.018 | 1.035 | Gouveia et al. (2003) |
| $SO_2$ | 1.024 | 1.013 | |
| $O_3$ | 1.008 | 1.009 | Gouveia et al. (2006) |
| $PM_{2.5}$ | 1.0382 (lag 0) | – | Nascimento et al. (2017) |
| | 1.056 (lag 5) | – | |
| Belo Horizonte | | | |
| $PM_{10}$ | 1.024 | 1.022 | Gouveia et al. (2006) |
| $SO_2$ | 1.067 | 1.113 | |
| $O_3$ | 1.008 | 1.009 | |
| $PM_{2.5}$ | 1.0382 (lag 0) | – | Nascimento et al. (2017) |
| | 1.056 (lag 5) | – | |
| All ages—for all cities | | | |
| $PM_{10}$ | 1.0967 | | Freitas et al. (2016) |
| $SO_2$ | 1.0698 | | |
| $O_3$ | 1.0193 | | |
| $PM_{2.5}$ | 1.085 | | Ferreira et al. (2016) |

epidemiological study, the RR was considered differently; when it was not, the same RR was used for both lags.

Hourly air quality monitoring data was obtained from the environmental agencies of each state and the daily concentrations were calculated according to the AQS. It was necessary to process the monitoring data to match morbidity data frequency format, which associates a daily number of hospital admissions to a city. Therefore, the average value of all hourly monitoring station values within its area in a day was used to prepare daily concentrations to be associated with each city (Andreão et al. 2018).

Finally, economic gains deriving from the avoided hospital admissions were estimated using the mean value paid for a hospital admission (all costs), also obtained from DATASUS (DATASUS 2019). Monthly values were used, according to

**Fig. 2** Number of hospital admissions of children (< 5 years old) and the elderly (> 64 years old) due to respiratory diseases for the four cities and investigated years




the age group, and then multiplied by the number of avoided hospital admissions estimated for the same period.

## Diagnostic of the air quality and its human health effects

### Air quality monitoring data

It is known that some monitoring stations are usually more sensitive to relevant air pollution sources than others (Andrade et al. 2017). Vitória is an example, where a significant variation was observed between pollutant concentration obtained in different monitoring stations. Thus, a spatially averaged concentration may not necessarily represent real air quality in a smaller scale.

Figure 3 presents 24-h $PM_{10}$ averages for the four cities within their respective periods of analysis. Regarding city-wide averaged levels, Vitória was the only city that did not exceed the final CONAMA standard of 50 μg m$^{-3}$. In all other cities, most standard exceedances occurred between May and October of each year, the winter period, when usually there is atmospheric stability due to the South Atlantic High-Pressure System positioned close to the continent. This anticyclonic circulation produces dry conditions, thermal inversion events and lower precipitation levels (Sun et al. 2017). In São Paulo, the AQS was exceeded 93 times from 2015 to 2018. In Rio de Janeiro, from 2014 to 2016, 61 daily $PM_{10}$ averages were above the final AQS. Belo Horizonte presented 30 exceedances in 2015, even though that year had 16 days without monitoring (maintenance). The highest concentration was recorded in Rio de Janeiro in 2017 (118.3 μg m$^{-3}$), which is below the current standard (IS-1, on Table 1), of 120 μg m$^{-3}$, but quite above the final standard (50 μg m$^{-3}$). In large urban areas, vehicle emissions are the dominant source of PM (Pacheco et al. 2017; Albuquerque et al. 2019) and they play a key role for an air quality improvement.

For $PM_{2.5}$, it can be observed in Fig. 4 that none of the cities were in compliance with the final national AQS (25 μg m$^{-3}$) in all 3 years, but the current applicable standard (60 μg m$^{3}$) was achieved. Similar to $PM_{10}$ results, most final standard exceedances occurred during winter months, especially in São Paulo and Belo Horizonte. In São Paulo, $PM_{2.5}$ was the pollutant with the most final standard exceedances: 160 from 2016 to 2018, which were linked to rainfall deficit associated with a predominance of a hot and dry air mass, atmospheric blockades that prevented cold fronts from entering the region, unfavorable weather conditions to dispersion, low ventilation and high percentage of calm, and biomass burning associated to the pollutants emissions by mobile and fixed sources (CETESB 2017; 2018; 2019). It also presented the highest annual average (16.9 μg m$^{-3}$ in 2018), whereas the smallest was found in Belo Horizonte in 2017 (9.5 μg m$^{-3}$). It is important to highlight that a high percentage of unavailable data was found for this pollutant: For Belo Horizonte in 2015, 42% of the days did not present $PM_{2.5}$ monitoring. $PM_{2.5}$ monitoring in Rio de Janeiro is performed manually every 6 days, which explains the fewer data points. It had 58 monitoring data points in 2015, 59 in 2016, and 52 in 2017, accounting for 16% of the days of the year in the first 2 years and 14% of 2017. The city only presented two exceedances in the years of analysis, which corroborates findings of authors such as Godoy et al. (2009), who had already

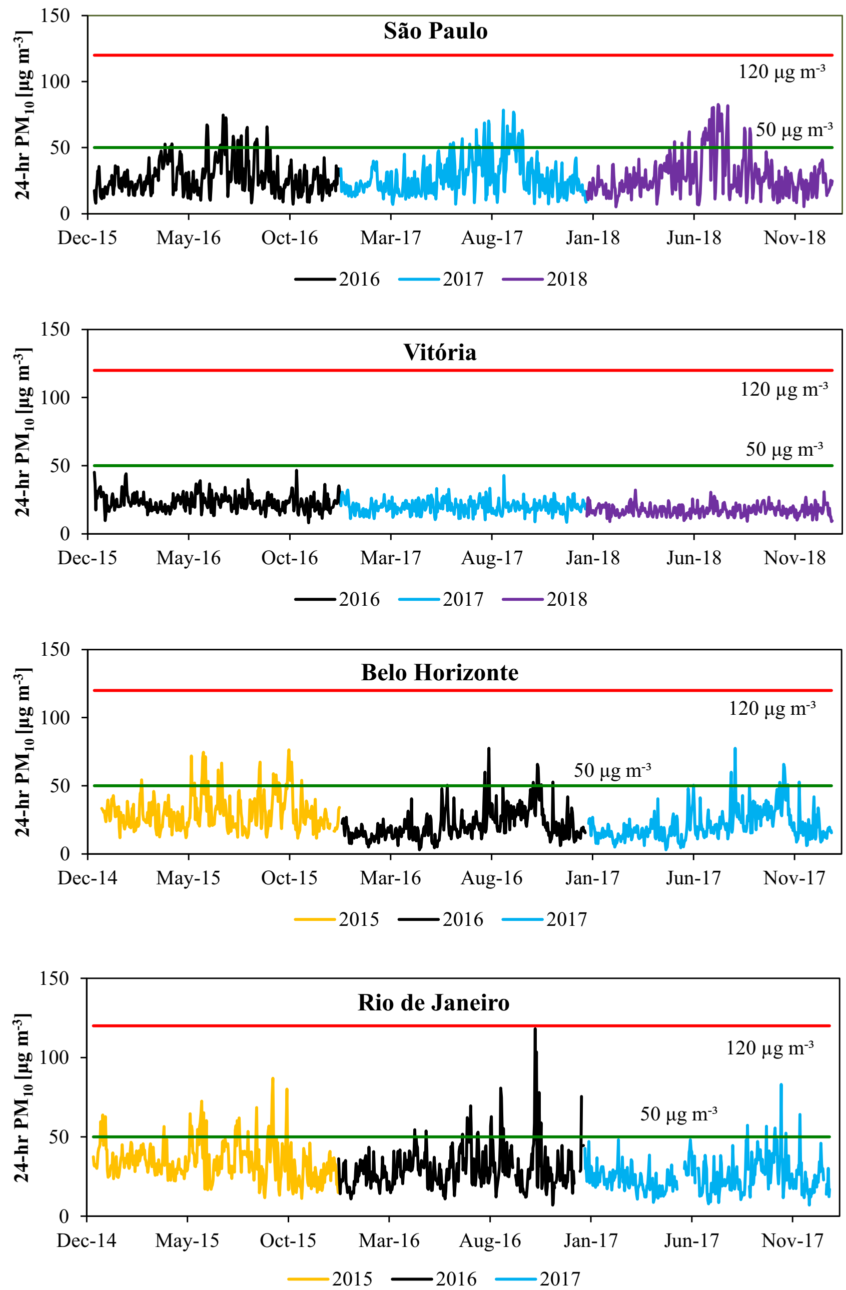



**Fig. 3** $PM_{10}$ 24-h averages for São Paulo, Vitória, Belo Horizonte, and Rio de Janeiro for the years considered for this study, respectively. Green line represents WHO guideline and final CONAMA AQS (50 µg m$^{-3}$), while the red line is the current (2019) AQS (120 µg m$^{-3}$)

identified that concentrations of particulate matter in Rio de Janeiro tend to be low.

For $O_3$, it can be observed in Fig. 5 that the final standard (MDA8 100 µg m$^{-3}$) was exceeded in all 3 years in São Paulo (114 exceedances). This pollutant has already been identified as attention point by Environmental Company of the state of São Paulo (CETESB 2018) due to the high levels of emissions of ozone precursors, especially from vehicular sources. In Vitória, no exceedances were recorded, but 34% of the data for 2016 was not available, during the final days of August and the end of December, when there are favorable conditions to ozone formation (spring and initial of summer). Only six exceedances were recorded in Belo Horizonte in 2015 and one in 2017. Exceedances were not found in Rio de Janeiro in 2015 and 2016, but $O_3$ concentrations were higher in 2017, registering 19 exceedances and the highest concentration for all cities (245.3 µg m$^{-3}$), in the beginning of spring.

Concerning $SO_2$, concentrations were found to be below the 24-h FS of 20 µg m$^{-3}$ during the clear majority period of analysis. Deviations were not registered in São Paulo and only one was found in Rio de Janeiro in 2016. In Vitória, there were peaks of concentration in 2017, from November 26th to December 8th, when the maximum concentration of 60.4 µg m$^{-3}$ was registered. However, annual average concentration was low: 6.0 µg m$^{-3}$.

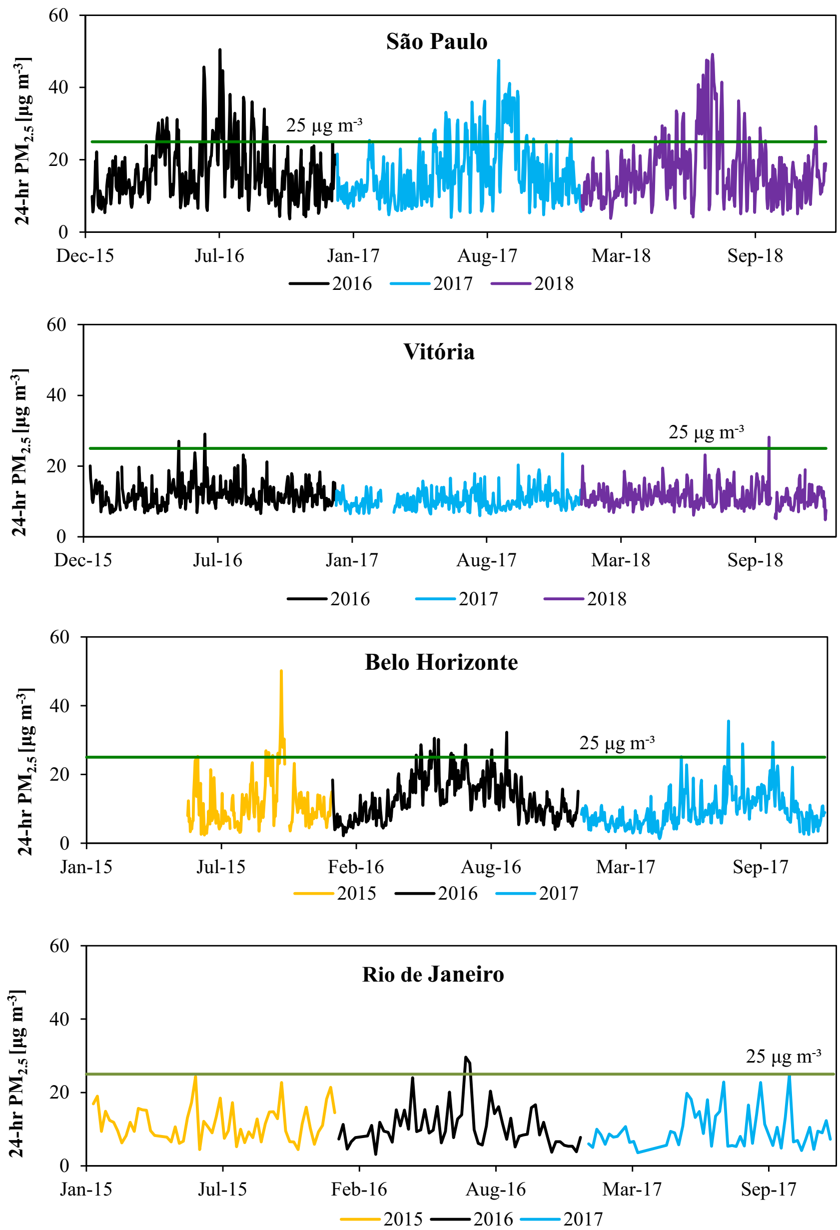



**Fig. 4** $PM_{2.5}$ 24-h averages of São Paulo, Vitória, Belo Horizonte, and Rio de Janeiro for the years considered for this study, respectively. Green line represents WHO guideline and final CONAMA standard (25 μg $m^{-3}$). Current applicable standard is 60 μg $m^{-3}$

Industrial activities in the region are the main sources of $SO_2$ (IEMA, 2019), and higher concentrations are observed in monitoring station more sensible to emissions from such industries (mainly due to the characteristic wind direction in the region). As for Belo Horizonte, peak concentrations occurred in 2015, from May 27th to June 6th, with a maximum concentration of 53.1 μg $m^{-3}$ and an annual average of 4.0 μg $m^{-3}$. These peaks were recorded by an automatic monitoring station located in Amazonas Avenue, the main avenue of the Metropolitan Region of Belo Horizonte. Santos (2018) showed that approximately 76% of $SO_2$ emissions in Belo Horizonte are from vehicular sources.

Regarding CO, all 8-h moving average concentrations in the four cities were found below the CONAMA Resolution 491/2018 standard (9 ppm) during the respective years of study. Highest concentrations were 2.5 ppm for Rio de Janeiro, in 2016; 2.0 ppm for Belo Horizonte, in 2015; 1.8 ppm for Vitória, in 2016 and 2.8 ppm in São Paulo, also in 2016. Since concentration levels of this pollutant are compliant with Brazilian legislation, monitoring data was disregarded in this study and no avoidable hospital admissions were estimated, although significant associations between CO levels and several health effects have been reported in epidemiological studies (Braga et al., 2001; Gouveia et al., 2006; Souza et al., 2018).

## Incidence rates

The incidence rate is calculated by dividing the daily average of hospital admissions by the population, here grouped per 10,000 inhabitants. Figure 6 presents the incident rate for respiratory

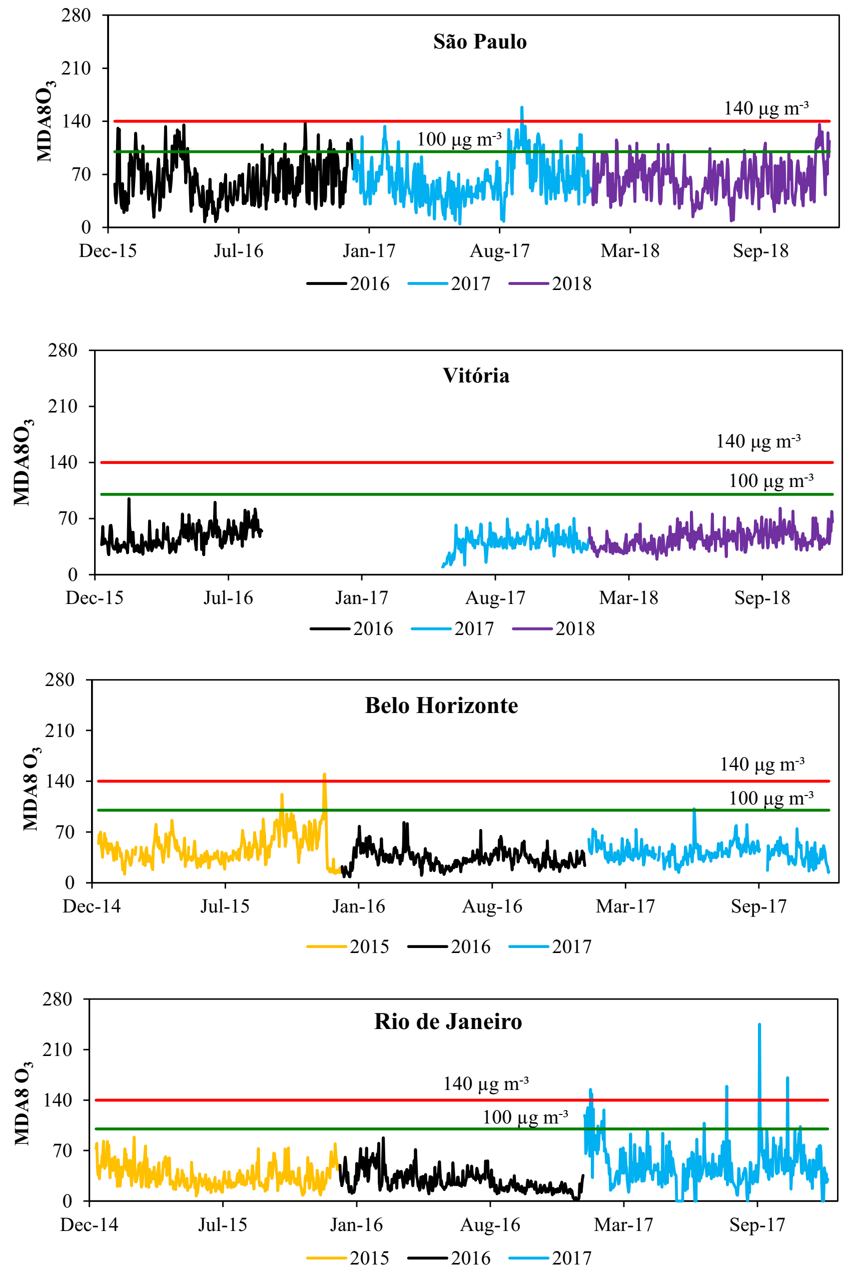



**Fig. 5** MDA8 $O_3$ monitoring data of São Paulo, Vitória, Belo Horizonte, and Rio de Janeiro for the years considered by this study, respectively. Green line represents WHO guideline and final CONAMA standard (100 µg m$^{-3}$) and red line the current standard (140 µg m$^{-3}$)

diseases in children (< 5 years old), elderly (> 64 years old), and all ages. Belo Horizonte presented the highest incidence rate of hospital admissions due to respiratory diseases in children and the elderly (26.9 in March/2015 and 25.2 in April /2015, per 10,000 inhabitants, respectively), followed by São Paulo. Rio de Janeiro had the lowest incidence rates for all years, in both age groups. Differences between the rates in each city are more pronounced when analyzing the elderly group. After March, the incidence rate increases, which may be related with the beginning of the dry season (April to September).

To estimate the avoidable admissions for all ages, the incidence rates were also calculated, but considering the total population and the total number of hospital admissions due to respiratory diseases. It can be noticed that the same pattern among cities remains, with Belo Horizonte presenting the highest incidence rates, followed by São Paulo, Vitória and, finally, Rio de Janeiro with the lowest values. Overall, the incidence in elders and children is bigger than considering all ages, where the biggest rate calculated was below 6 admissions per 10,000 inhabitants.

## Estimation of avoidable hospital admissions

Figure 7 shows the estimated hospital admissions due to respiratory diseases that would have been avoided if ambient levels of $PM_{10}$, $MP_{2.5}$, $O_3$, and $SO_2$ were at the levels of the

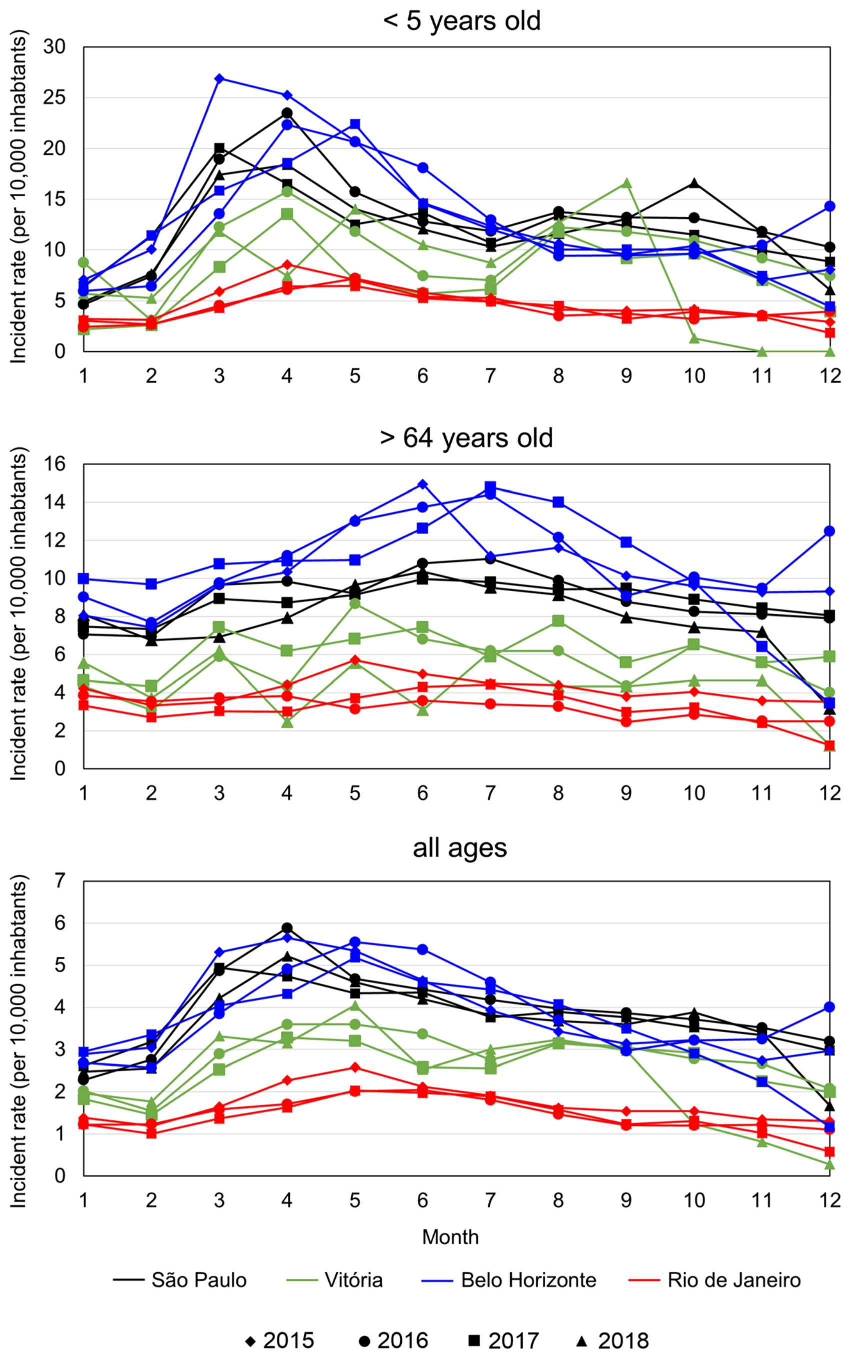



**Fig. 6** Incident rate for respiratory diseases in children (< 5 years old), elderly (> 64 years old), and all ages

final standard of the new Brazilian AQS in all four cities, considering the period from 2015 to 2017 in Belo Horizonte and Rio de Janeiro and from 2016 to 2018 in São Paulo and Vitória. The levels of CO did not exceed the final standard in any city, and therefore, no avoidable hospital admissions were recorded for this pollutant. The number of hospital admissions consists of the sum of the results for both age groups (children and elderly). Overall, results considering the day of exposure (lag 0) were superior to those with the 5-day moving average (lag 5).

The highest numbers of avoidable hospital admissions for $PM_{10}$ and $PM_{2.5}$ were found in São Paulo. According to the 2017 CETESB air quality report (CETESB 2018), annual PM mean concentrations presented a downward trend since 2015. However, estimated number of avoidable hospital admissions increased from 2016 to 2018 for both $PM_{10}$ and $PM_{2.5}$. This is related to the daily averages used in the estimations. In 2017, higher levels of PM were recorded in September, a month in which adverse meteorological conditions to the dispersion of pollutants were registered in the city (CETESB 2018).

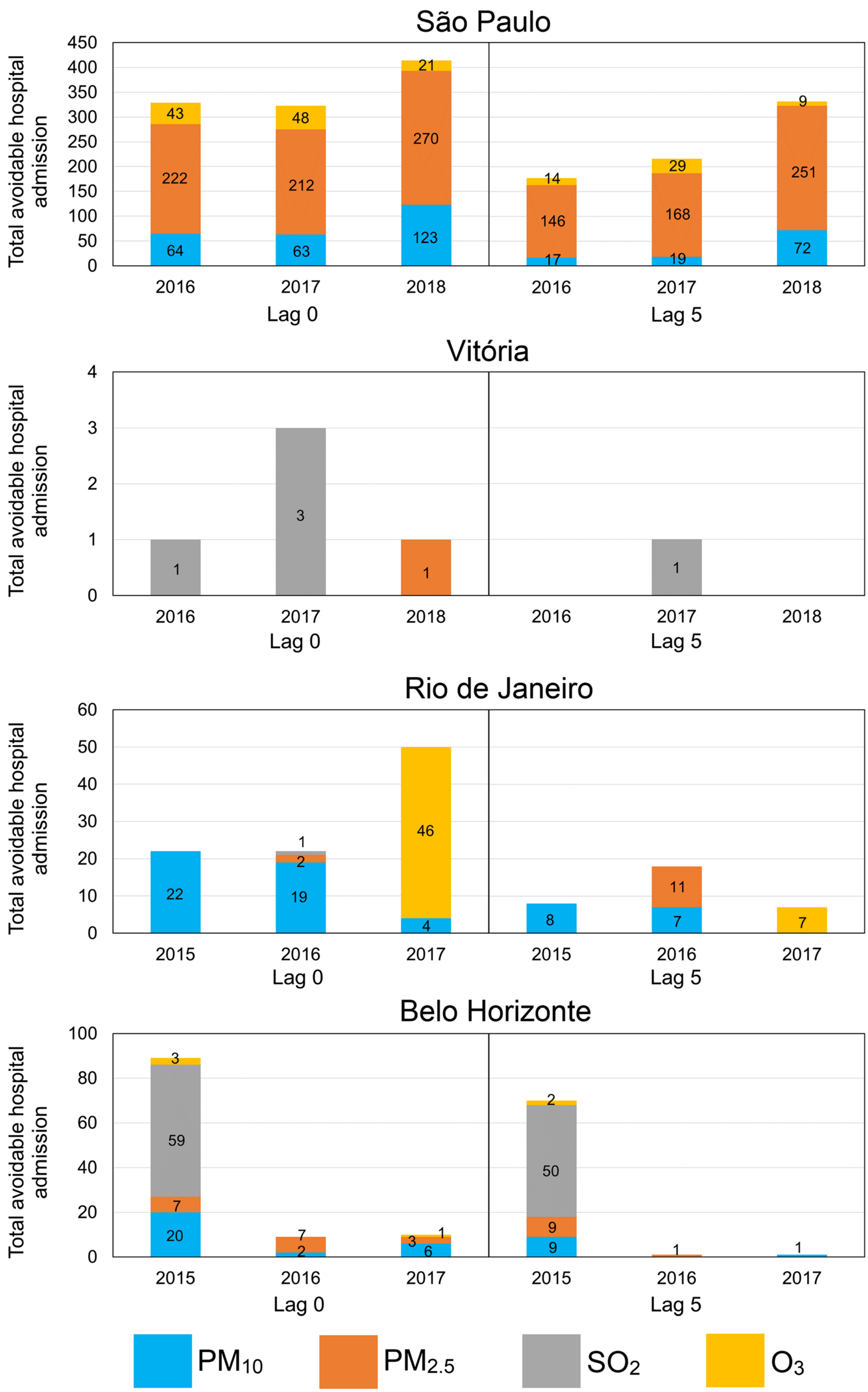



**Fig. 7** Total avoided hospital admissions in all analyzed cities. The numbers correspond to sum of the avoidable admissions calculated for children (< 5 years old) and elderly (> 64 years old)

**Table 6** Total cost of the avoidable hospital admissions per city for all ages

| City | Avoidable hospital admissions (all ages) | | Cost of the hospital admissions (USD)[c] | |
|---|---|---|---|---|
| | Lag-0 | Lag-5 | Lag-0 | Lag-5 |
| São Paulo[a] | 3454 | 1726 | $906,509.81 | $321,432.69 |
| Vitória[a] | 9 | 1 | $1218.31 | $180.38 |
| Rio de Janeiro[b] | 399 | 118 | $109,899.07 | $25,941.88 |
| Belo Horizonte[b] | 286 | 168 | $73,801.94 | $58,593.43 |
| Total | 4148 | 2013 | $1,091,429.12 | $406,148.38 |

[a] 2016 to 2018

[b] 2015 to 2017

[c] The USD/BRL rate used was 4.00

Almost 20 (CI 15 to 30) and 22 (CI 15 to 44) avoided admissions (lag-0) in 2015 were estimated to Belo Horizonte and Rio de Janeiro, respectively. Although $PM_{10}$ concentrations in these two cities were generally lower than in São Paulo, results are similar when results are analyzed in relation to 100,000 inhabitants, especially in Belo Horizonte, the least populated among the three cities. In relative numbers, three avoidable admissions for each 100,000 inhabitants were estimated in São Paulo (2016 and 2017, lag-0) and four admissions for each 100,000 inhabitants in Belo Horizonte (2015, lag-0). These results are probably due to the higher incidence rates in Belo Horizonte (Fig. 6), which contributed to an increase in the number of avoided hospital admissions.

The highest number of avoidable hospital admissions was calculated for $PM_{2.5}$ in 2018 in São Paulo: 270 (CI 0 to 590) for lag-0; and 251 (CI 24 to 472) for lag-5. The results in São Paulo were well above the other cities, as expected considering the air quality monitored levels (Fig. 4).

Regarding $O_3$, even though the highest ambient ozone levels were found in São Paulo (Fig. 5), results in Rio de Janeiro were in a similar range, with 46 (CI 30 to 73) admissions avoided in 2018 (lag-0). In relative numbers, the highest number of avoidable hospital admissions for ozone was calculated for Rio de Janeiro: 4 for each 100,000 inhabitants (2017, lag-0). According to the Environmental Agency of the state of Rio de Janeiro, ozone emissions are mostly linked to the dense flow of vehicles and petrochemical industry activities, emitting more $NO_x$ and hydrocarbons (INEA 2016). A reduction in emissions of ozone precursors, mainly associated with fossil fuel combustion from vehicle sources (Andrade et al. 2017; Pacheco et al. 2017), can benefit air quality and help decrease tropospheric ozone levels.

Public health gains for $SO_2$ were greater in Belo Horizonte, where 59 (CI 50 to 75) admissions, considering the lag-0, and 50 (CI 8 to 13) considering the lag-5, would be avoided in 2015. However, as discussed before, $SO_2$ levels were not a concern for any of the cities, and standard exceedances registered in Belo Horizonte were due to high concentration peaks condensed in few days at the end of May 2015.

Compared to the other cities, small numbers of avoided hospital admissions were found in Vitória. This is not unexpected, given that air quality monitored levels in the city were found to be compliant with standards for the majority of the 3 years of analysis (maybe due to the lower number of air quality monitoring stations). However, the elevated incidence rates and RR reported for the city indicate that pollutants may affect public health even in low concentrations in the city.

Considering all pollutants investigated, the total avoidable hospital admissions of children and elderly in the periods

**Table 7** Total cost of the avoidable hospital admissions per city

| City | Avoidable hospital admissions (children and elderly) | | Cost of the hospital admissions (USD)[c] | |
|---|---|---|---|---|
| | Lag-0 | Lag-5 | Lag-0 | Lag-5 |
| São Paulo[a] | 1066 | 725 | $281,369.24 | $132,799.87 |
| Vitória[a] | 5 | 1 | $1162.25 | $263.54 |
| Rio de Janeiro[b] | 94 | 33 | $30,406.62 | $7191.36 |
| Belo Horizonte[b] | 108 | 72 | $40,516.1 | $27,742.29 |
| Total | 1273 | 831 | $353,454.62 | $167,997.06 |

[a] 2016 to 2018

[b] 2015 to 2017

[c] The USD/BRL rate used was 4.00

analyzed was 1066 (lag-0) and 725 (lag-5) in São Paulo, 94 (lag-0) and 33 (lag-5) in Rio de Janeiro, 108 (lag-0) and 72 (lag-5) in Belo Horizonte, and 5 (lag-0) and 1 (lag-5) in Vitória, which represent up to 1% of the total number of the hospital admissions, being the highest in São Paulo, 1% (lag-0) and 0.68% (lag-5), and the smallest in Vitória, 0.10% (lag-0) and 0.02% (lag-5).

To put these results into context, the same methodology was followed to calculate the results considering the whole population (all ages), presented in Table 6. Even though the elderly and children represent between 15% and 18% of the population in all four cities, the avoidable hospital admissions in those groups represent 31% (lag-0) and 41% (lag-5) of the total. The result supports the observation that children and elderly are more susceptible to air pollution.

To calculate the cost of the avoidable hospital admissions, the total value of admission (included expenses such as values of hospital services, medicine, professionals) was used, as found in DATASUS. According to the database, Belo Horizonte has the highest mean value paid for hospital admission in the Public Health System. Based on the total number of hospital admissions avoided, the total avoided expending derived from these public health gains is \$353,454.62 (for children and elderly), considering admissions caused by same-day exposure. The cost by city is presented in Table 7. Although not investigated, between 2016 and 2018, in São Paulo and Vitória, and between 2015 and 2017, in Belo Horizonte and Rio de Janeiro, cardiovascular diseases cost around three times higher than respiratory diseases. Considering that an improvement in air quality will also bring a reduction in cardiovascular hospital admissions, the monetary gain will be considerable higher than those presented.

Regarding mortality, Andreão et al. (2018) showed between 1284 and 3379 avoidable deaths due to all causes in São Paulo in 2017 if the $PM_{2.5}$ annual WHO guideline (10 μg m$^{-3}$) was met. Non-accidental causes accounted for between 1615 and 5634 deaths, cardiovascular between 775 and 1932 avoidable deaths, and lung cancer between 55 and 144 avoidable deaths, according to the cohort study used. Rio de Janeiro accounted for between 453 and 1162 all cause avoidable deaths, while Belo Horizonte presented all causes avoidable deaths between 87 and 246 in 2013 and between 149 and 410 in 2014. Due to a $PM_{2.5}$ annual concentration close to WHO guideline in Vitória, the benefits were lower than 10 avoidable deaths.

## Conclusions

The goal of this study was to estimate public health benefits of complying with the new final Brazilian air quality standard in the state capitals of the Southeast region of Brazil, focusing on the respiratory effect on children (< 5 years old), the elderly (> 64 years old), and all ages. Data on total population, hospital admissions due to respiratory diseases and air quality monitoring were gathered for the four analyzed cities: São Paulo, Rio de Janeiro, Vitória, and Belo Horizonte.

São Paulo and Rio de Janeiro presented an extensive air quality monitoring network, whereas Vitória and Belo Horizonte have only three and two stations, respectively. This highlights the importance of expanding the monitoring network in urban centers, as it provides essential data needed to activate emergency actions during periods of atmospheric stagnation, assess local air quality against the established standards designed to protect public health and well-being, and monitor trends and changes in air quality due to changes in pollutant emissions.

The datasets were collected for years 2016 to 2018 for São Paulo and Vitória and 2015 to 2017 for Rio de Janeiro and Belo Horizonte. Regarding air quality monitoring, most standard exceedances occurred between May and October, corresponding to the dry season in the region, where atmospheric stability is common. Overall, most final standard exceedances of $PM_{10}$, $PM_{2.5}$, and $O_3$ were registered in São Paulo, while $SO_2$ was identified as a pollutant of interest in Belo Horizonte and Vitória.

A literature review on RR showed that most epidemiological studies concentrate in the Southeast region and only in a few specific cities. Therefore, even though these factors are the best available information, its lack of representation bring uncertainties to the use of factors derived from such studies in the evaluation of health gains through air quality improvements in other regions. Epidemiological studies focusing on air pollution in a wider range of Brazilian cities are necessary to enable estimations of public health benefits of public policies and enforce the necessity of such measures. Moreover, epidemiological studies regarding other health outcomes, as cardiovascular diseases, are still necessary for Brazilian cities.

The estimates of avoided hospital admissions agreed with expectations from observations in air quality monitoring data. Overall, the larger number of avoidable hospital admissions was estimated for São Paulo, considering final CONAMA standards. In spite of having largest population among the four, the city has low incidence rate, when compared to Vitória and Belo Horizonte, and presented the largest number days with AQS deviations, which justify the results. Most of the avoidable admissions were due to $PM_{2.5}$, being 704 from 2016 to 2018, considering the same-day effects (lag-0). São Paulo also presented the highest avoidable admissions for $PM_{10}$ (123 in 2018; lag-0). The estimated number of hospital admissions due to $PM_{10}$ in Belo Horizonte show the importance of considering actions to reduce particulate matter levels. However, the highest number of avoidable respiratory admissions found in Belo Horizonte was associated with $SO_2$ (59 and 50 avoidable admissions in 2015, considering the lag-0 and lag-5 respectively), due to concentration peaks observed in that same year.

Rio de Janeiro presented 46 (lag-0) avoidable admissions for $O_3$ in 2017, showing the impact of ambient ozone levels in that year. Continuous update and evaluation of data from air quality monitoring stations are necessary to investigate if ozone levels in Rio de Janeiro will continue to resemble concentrations found in 2017, as this pollutant can be a potential threat to public health. Vitória did not present a representative number of avoided hospital admissions, as air quality levels in the city were already compliant with legislation for most pollutants. But, when a single monitoring station is considering, exceeds may occur.

When looking at the avoidable hospital admissions for all ages, the result for under five and over 64 years old corresponds to 31% (lag-0) and 41% (lag-5) of the total, which highlights the severe effect air pollution has on those groups. Overall, up to 1% of the total respiratory disease-related admissions of elderly and children was estimated to be avoidable by lowering pollution levels to match the final AQS. The avoidances can lead to savings of $353,454.62 in public health spending, considering the same-day effect. For all ages, the avoidable hospital admission corresponded to 1.5% of the total hospitalizations.

Significant public health gains, including economic, are achieved adopting more restrictive air quality standards, with clear goals, and a well-established deadline to reach the final standards. Stablishing and enforce a deadline for implementing the most stringent standards is the first action necessary in Brazil. Public policies are important so that intermediate goals of the new nation-wide AQS resolution are progressively met in the whole Brazilian territory, bringing about public health and cost savings to states. Improvements should include expanding the air quality monitoring network, mapping of the sources in each location and understanding the causes of air pollution and epidemiological studies to understand the consequences. Reducing air pollutants concentration, more avoided hospital admissions due other outcomes, as cardiovascular diseases, may be expected. As mortality is usually related to long-term exposure, avoidable mortality may also be expected reducing daily air pollutants concentration, as showed by Andreão et al. (2018).

Among the analyzed cities, air quality in São Paulo and, consequently, avoided hospital admissions would improve a lot through the reduction of ambient particulate matter and ozone concentrations. According to Franco et al. (2019), Latin-American cities such as Santiago and Mexico City have achieved lowering $PM_{10}$ concentrations by moving towards cleaner energy use and a compensation system to promote emission reduction. The authors also identified that better public policies in Brazilian cities are needed, as they pointed limitations on São Paulo and Belo Horizonte as linked to poor handling of the topic by public authorities.

To improve the representativeness of the results, more precise spatial distribution linking air pollution and hospital admissions is also recommended, considering the demographics of each area and the spatial representativeness of each station. In future studies, we recommend assessing additional health benefits of stricter air quality standards, including avoided hospital admissions due to cardiovascular diseases and avoided premature mortality, to better understand the full range of public health benefits that stricter air quality standards provide.

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## References

Agudelo-Castañeda DM, Teixeira EC, Alves L, Fernández-Niño JA, Rodríguez-Villamizar LA (2019) Monthly-term associations between air pollutants and respiratory morbidity in South Brazil 2013–2016: a multi-city, time-series analysis. Int J Environ Res Public Health 16:3787. https://doi.org/10.3390/ijerph16203787

Albuquerque TT, West J, Andrade MF et al (2019) Analysis of PM 2.5 concentrations under pollutant emission control strategies in the metropolitan area of São Paulo, Brazil. Environ Sci Pollut Res 26(32):33216–33227

Andrade MF, Kumar P, de Freitas ED, Ynoue RY, Martins J, Martins LD et al (2017) Air quality in the megacity of São Paulo: evolution over the last 30 years and future perspectives. Atmos Environ 159:66–82

Andreão WL, Albuquerque TT, Kumar P (2018) Excess deaths associated with fine particulate matter in Brazilian cities. Atmos Environ 194: 71–81

Araújo MRM, Oliveira JM, Jesus MS, Sá NR, Santos PAC, Lima TC (2011) Transporte público coletivo: discutindo acessibilidade, mobilidade e qualidade de vida. Psicologia & Sociedade 23(3): 574–582

Arbex MA, Santos UDP, Martins LC, Saldiva PHN, Pereira LAA, Braga ALF (2012) A poluição do ar e o sistema respiratório. J Bras Pneumol 38(5):643–655

Bakonyi SMC, Danni-Oliveira IM, Martins LC, Braga ALF (2004) Poluição atmosférica e doenças respiratórias em crianças na cidade de Curitiba, PR. Rev Saude Publica 38:695–700

Boldo E, Linares C, Aragonés N, Lumbreras J, Borge R, de la Paz D, Pérez-Gómez B, Fernández-Navarro P, García-Pérez J, Pollán M, Ramis R, Moreno T, Karanasiou A, López-Abente G (2014) Air quality modeling and mortality impact of fine particles reduction policies in Spain. Environ Res 128:15–26

Braga ALF, Conceição GM, Pereira LA, Kishi HS, Pereira JC, Andrade MF et al (1999) Air pollution and pediatric respiratory hospital admissions in São Paulo. Brazil J Environ Med 1:95–102

Braga ALF, Pereira LAA, Procópio M, André PAD, Saldiva PHDN (2007) Association between air pollution and respiratory and cardiovascular diseases in Itabira, Minas Gerais State, Brazil. Cadernos de Saúde Pública 23:S570–S578

Braga ALF, Saldiva PH, Pereira LA, Menezes JJ, Conceição GM, Lin CA, Zanobetti A, Schwartz J, Dockery DW (2001) Health effects of air pollution exposure on children and adolescents in São Paulo, Brazil. Pediatr Pulmonol 31:106–113

Cançado JE, Saldiva PH, Pereira LA, Lara LB, Artaxo P, Martinelli LA, Arbex MA, Zanobetti A, Braga AL (2006) The impact of sugar cane–burning emissions on the respiratory system of children and the elderly. Environ Health Perspect 114(5):725–729

Carmo CND, Hacon S, Longo KM, Freitas S, Ignotti E, Leon APD, Artaxo P (2010) Associação entre material particulado de queimadas e doenças respiratórias na região sul da Amazônia brasileira. Rev Panam Salud Publica 27:10–16

Castro HAD, Cunha MFD, Mendonça GA, Junger WL, Cunha-Cruz J, Leon APD (2009) Effect of air pollution on lung function in schoolchildren in Rio de Janeiro, Brazil. Rev Saude Publica 43(1): 26–34

César ACG, Nascimento LFC, Carvalho JAD Jr (2013) Association between exposure to particulate matter and hospital admissions for respiratory disease in children. Rev Saude Publica 47(6):1209–1212

CETESB – Environmental Company of the State of São Paulo (2017) Qualidade do Ar no Estado de São Paulo – 2016. São Paulo, Brazil

CETESB – Environmental Company of the State of São Paulo (2018) Qualidade do Ar no Estado de São Paulo – 2017. São Paulo, Brazil

CETESB – Environmental Company of the State of São Paulo (2019) Qualidade do Ar no Estado de São Paulo – 2018. São Paulo, Brazil

Cortizo EC (2002) Mecanismos de avaliação ambiental: Estudo de caso Belvedere III, município de Belo Horizonte. Pontifícia Universidade Católica de MG, MSc Dissertation

DATASUS (2019) Brasil (2019) "Departamento de Informática do SUS.". Ministério de Saúde do Brasil

Farhat SCL, Paulo RLP, Shimoda TM, Conceição GMDS, Lin CA, Braga ALF, Warth MPN, Saldiva PHN (2005) Effect of air pollution on pediatric respiratory emergency room visits and hospital admissions. Braz J Med Biol Res 38(2):227–235

Ferreira T, Forti M, de Freitas C, Nascimento F, Junger W, Gouveia N (2016) Effects of particulate matter and its chemical constituents on elderly hospital admissions due to circulatory and respiratory diseases. Int J Environ Res Public Health 13(10):947

Franco JF, Gidhagen L, Morales R, Behrentz E (2019) Towards a better understanding of urban air quality management capabilities in Latin America. Environ Sci Pol 102:43–53

Freitas C, Bremner SA, Gouveia N, Pereira LA, Saldiva PH (2004) Internações e óbitos e sua relação com a poluição atmosférica em São Paulo, 1993 a 1997. Rev Saude Publica 38:751–757

Freitas CUD, Junger W, Leon APD, Grimaldi R, Silva MAFR, Gouveia N (2013) Poluição do ar em cidades brasileiras: selecionando indicadores de impacto na saúde para fins de vigilância. Epidemiologia e Serviços de Saúde 22(3):445–454

Freitas CUD, Leon APD, Juger W, Gouveia N (2016) Poluição do ar e impactos na saúde em Vitória. Espírito Santo Rev Saúde Pública 50: 4

Freitas ED, Rozoff CM, Cotton WR, Dias PLS (2007) Interactions of an urban heat island and sea-breeze circulations during winter over the metropolitan area of São Paulo, Brazil. Bound-Layer Meteorol 122: 43–65

Galvão ES, Reis NC Jr, Lima AT, Stuetz RM, MTD'A O, Santos JM (2019) Use of inorganic and organic markers associated with their directionality for the apportionment of highly correlated sources of particulate matter. Sci Total Environ 651:1332–1343

Godoy MLDP, Godoy JM, Roldão LA, Soluri DS, Donagemma RA (2009) Coarse and fine aerosol source apportionment in Rio de Janeiro, Brazil. Atmos Environ 43:2366–2374

Gonçalves KDS, Castro HAD, Hacon SDS (2012) As queimadas na região amazônica e o adoecimento respiratório. Ciência & Saúde Coletiva 17:1523–1532

Gouveia N, Corrallo FP, de Leon ACP, Junger W, de Freitas CU (2017) Poluição do ar e hospitalizações na maior metrópole brasileira. Rev Saude Pública 51:1–10. https://doi.org/10.11606/S1518-8787.2017051000223

Gouveia N, Fletcher T (2000a) Time series analysis of air pollution and mortality: effects by cause, age and socioeconomic status. J Epidemiol Community Health 54(10):750–755

Gouveia N, Fletcher T (2000b) Respiratory diseases in children and outdoor air pollution in Sao Paulo, Brazil: a time series analysis. Occup Environ Med 57(7):477–483

Gouveia N, Freitas CUD, Martins LC, Marcilio IO (2006) Respiratory and cardiovascular hospitalizations associated with air pollution in the city of São Paulo, Brazil. Cadernos de Saúde Pública 22(12): 2669–2677

Gouveia N, Leon AP, Junger W, Lins JDF, Freitas CU (2019) Air pollution and the impacts on health in the Metropolitan Region of Belo Horizonte in the state of Minas Gerais, Brazil. Ciencia & Saude Coletiva 24(10):3773–3781. https://doi.org/10.1590/1413-812320182410.29432017

Gouveia N, Mendonça GA, Leon APD, Correia JEDM, Junger WL, Freitas CUD et al (2003) Air pollution and health effects in two Brazilian Metropolis. Epidemiologia e Serviços de Saúde 12(1): 29–40

IBGE – Brazilian Institute of Geography and Statistics (2018) Produto Interno Bruto – PIB https://www.ibge.gov.br/explica/pib.php . Accessed in 05 July 2019

IBGE – Brazilian Institute of Geography and Statistics (2019a) Cidades – São Paulo. https://cidades.ibge.gov.br/brasil/sp/sao-paulo/panorama. Accessed in 05 July 2019

IBGE – Brazilian Institute of Geography and Statistics (2019b) Cidades – Rio de Janeiro. https://cidades.ibge.gov.br/brasil/rj/rio-de-janeiro/panorama. Accessed in 05 July 2019

IBGE – Brazilian Institute of Geography and Statistics (2019c) Cidades – Belo Horizonte. https://cidades.ibge.gov.br/brasil/mg/belo-horizonte/panorama. Accessed in 05 July 2019

IBGE – Brazilian Institute of Geography and Statistics (2019d) Cidades – Vitória. https://cidades.ibge.gov.br/brasil/es/vitoria/panorama. Accessed in 05 July 2019

IEMA – Energy and Environment Institute (2014) 1º Diagnóstico da rede de monitoramento da qualidade do ar no Brasil. São Paulo: Instituto de Energia e Meio Ambiente

IEMA – Environmental Company of the state of Espírito Santo (2019) Inventário de emissões atmosféricas Região da Grande Vitória ano-base 2015. Vitória: IEMA/EcoSoft

INEA - State Institute of the Environment (2016) Relatório da Qualidade do Ar do Estado do Rio de Janeiro - Ano Base 2015Rio de Janeiro, Brazil1http://www.inea.rj.gov.br/wp-content/uploads/2019/01/RQAr_2015.pdfINEA - State Institute of the Environment (2016) Relatório da Qualidade do Ar do Estado do Rio de Janeiro - Ano Base 2015. *Rio de Janeiro, Brazil*, 1, http://www.inea.rj.gov.br/wp-content/uploads/2019/01/RQAr_2015.pdf (2016).

Ignotti E, Hacon SDS, Junger WL, Mourão D, Longo K, Freitas S et al (2010) Air pollution and hospital admissions for respiratory diseases in the subequatorial Amazon: a time series approach. Cadernos de Saúde Pública 26:747–761

Jasinski R, Pereira LAA, Braga ALF (2011) Air pollution and pediatric hospital admissions due to respiratory diseases in Cubatão, São Paulo State, Brazil, from 1997 to 2004. Cadernos de Saúde Pública 27(11):2242–2252

Lessa DA, Miranda GC, Lobo C, Cardoso L (2019) A mobilidade urbana em Belo Horizonte/Minas Gerais/Brasil: indicadores e projeções para as viagens por automóveis. Revista Transporte y Territorio 20:288–306

Machin AB, Nascimento LFC (2018) Efeitos da exposição a poluentes do ar na saúde das crianças de Cuiabá, Mato Grosso, Brasil. Cadernos de Saúde Pública 34:3

Martins LC, Latorre MDRDD, Cardoso MRA, Gonçalves FLT, Saldiva PHN, Braga ALF (2002) Air pollution and emergency room visits due to pneumonia and influenza in Sao Paulo, Brazil. Rev Saude Publica 36(1):88–94

Miranda RM, Andrade MF, Fornaro A, Astolfo R, Andre PA, Saldiva P (2012) Urban air pollution: a representative survey of PM2.5 mass concentrations in six Brazilian cities. Air Qual. Atmos. Health 5:63–77

Moura M, Junger WL, Leon APD (2009) Air quality and emergency pediatric care for symptoms of bronchial obstruction categorized by age bracket in Rio de Janeiro, Brazil. Cadernos de Saúde Pública 25:635–644

Nardocci AC, Freitas CUD, de Leon P, Monteiro AC, Junger WL, Gouveia NDC (2013) Air pollution and respiratory and cardiovascular diseases: a time series study in Cubatão, São Paulo State, Brazil. Cadernos de Saúde Pública 29(9):1867–1876

Nascimento AP, Santos JM, Mill JG, de Souza JB, Júnior NCR, Reisen VA (2017) Associação entre concentração de partículas finas na atmosfera e doenças respiratórias agudas em crianças. Rev Saude Publica 51:3–3

Nascimento LFC, Pereira LAA, Braga AL, Módolo MCC, Carvalho JA Jr (2006) Efeitos da poluição atmosférica na saúde infantil em São José dos Campos, SP. Rev Saude Publica 40:77–82

Negrisoli J, Nascimento LFC (2013) Atmospheric pollutants and hospital admissions due to pneumonia in children. Rev Paul Pediatr 31(4): 501–506

Nogueira T, Cordeiro DS, Munoz RAA, Fornaro A, Miguel AH, Andrade MF (2015) Bioethanol and biodiesel as vehicular fuels in Brazil - assessment of atmospheric impacts from the long period of biofuels use. Biofuels – Status and Perspective. InTech, In. https://doi.org/10.5772/60944

Nogueira T, Dominutti PA, De Carvalho LRF, Fornaro A, Andrade MDF (2014) Formaldehyde and acetaldehyde measurements in urban atmosphere impacted by the use of ethanol biofuel: metropolitan area of Sao Paulo (MASP), 2012-2013. Fuel 134:505–513

Onursal B, Gautam SP (1997) Vehicular air pollution: experiences from seven Latin American urban centres. World Bank Technical Paper No. 373, Washington

Pacheco MT, Parmigiani MMM, de Fatima AM, Morawska L, Kumar P (2017) A review of emissions and concentrations of particulate matter in the three major metropolitan areas of Brazil. J Transp Health 4: 53–72

Pope CA III, Coleman N, Pond ZA, Burnett RT (2019) Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ Res 108924. https://doi.org/10.1016/j.envres.2019.108924

Rodriguez CAM, Rocha RP, Bombardi R (2010) On the development of summer thunderstorms in the city of São Paulo: mean meteorological characteristics and pollution effect. Atmos Res 96:477–488

Sacks JD, Lloyd JM, Zhu Y, Anderton J, Jang CJ, Hubbell B, Fann N (2018) The environmental benefits mapping and analysis program–community edition (BenMAP–CE): a tool to estimate the health and economic benefits of reducing air pollution. Environ Model Softw 104:118–129

Salvi SS, Barnes PJ (2009) Chronic obstructive pulmonary disease in non-smokers. Lancet 374(9691):733–743

Santos FS, Miranda GA, Carvalho AMN, Carvalho VSB, Albuquerque TT (2019) Regulated air pollutant emissions from higher emitters stationary sources in Belo Horizonte, Minas Gerais, Brazil. Braz J Chem Eng 36(2). https://doi.org/10.1590/0104-6632.20190362s20180352

Santos FS (2018) Diagnóstico das emissões atmosféricas em Minas Gerais: um estudo para as fontes fixas e veiculares. Federal University of Minas Gerais, MSc Dissertation

Silva AMCD, Mattos IE, Ignotti E, Hacon SDS (2013) Particulate matter originating from biomass burning and respiratory. Rev Saude Publica 47(2):345–352

SISMOB-BH – System of information about accessibility and sustainability in Belo Horizonte (2015) Indicadores Populacionais. Prefeitura de Belo Horizonte https://prefeiturapbhgovbr/sites/default/files/imagens/authenticated%2C%20editor_a_bhtrans/item2_2_SisMobBH_DadosAbertos_Frota%20e%20condutores%20de%20ve%C3%ADculos%20automotores_2017_01_23pdf Acessed 10 August 2019

Soluri DS, Godoy MLDP, Godoy JM, Roldao LA (2007) Multi-site PM2.5 and PM2.5-10 aerosol source apportionment in Rio de Janeiro. Brazil Braz Chem Soc 18:838–845

Souza JB, Reisen VA, Franco GC, Ispány M, Bondon P, Santos JM (2018) Generalized additive models with principal component analysis: an application to time series of respiratory disease and air pollution data. Appl Statist 67(2):453–480

Souza LSVD, Nascimento LFC (2016) Air pollutants and hospital admission due to pneumonia in children: a time series analysis. Rev Assoc Med Bras 62(2):151–156

Sun X, Cook KH, Vizy EK (2017) The South Atlantic subtropical high: climatology and interannual variability. J Clim 30:3279–3296

The World Bank (2019) Urban population (% of total) https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS .Accessed in 31 July 2019

United Nations, Department of Economic and Social Affairs (2015) Population Division, 2015. World Urbanization Prospects: the 2014 revision. ST/ESA/SER.A/366

Vasconcellos EA, Carvalho CHR, Pereira RHM (2011) Transporte e mobilidade urbana. CEPAL\IPEA, Brasília

Vilela JA (2007) Variáveis do clima urbano: análise da situação atual e prognósticos para a região do bairro Belvedere III. Federal University of Minas Gerais, MSc Dissertation

World Health Organization (1987) Air quality guidelines for Europe. WHO Regional Office for Europe, Copenhagen

World Health Organization (2006) Air quality guidelines: global update 2005. World Health Organization, Geneva

World Health Organization (2018) World health statistics 2018: monitoring health for the SDGs, sustainable development goals. World Health Organization, Geneva