Effect of particulate matter (PM$_{2.5}$ and PM$_{10}$) on health indicators: climate change scenarios in a Brazilian metropolis

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Abstract Recife is recognized as the 16th most vulnerable city to climate change in the world. In addition, the city has levels of air pollutants above the new limits proposed by the World Health Organization (WHO) in 2021. In this sense, the present study had two main objectives: (1) To evaluate the health (and economic) benefits related to the reduction in mean annual concentrations of PM$_{10}$ and PM$_{2.5}$ considering the new limits recommended by the WHO: 15 µg/m$^3$ (PM$_{10}$) and 5 µg/m$^3$ (PM$_{2.5}$) and (2) To simulate the behavior of these pollutants in scenarios with increased temperature (2 and 4 °C) using machine learning. The averages of PM$_{2.5}$ and PM$_{10}$ were above the limits recommended by the WHO. The scenario simulating the reduction in these pollutants below the new WHO limits would avoid more than 130 deaths and 84 hospital admissions for respiratory or cardiovascular problems. This represents a gain of 15.2 months in life expectancy and a cost of almost 160 million dollars. Regarding the simulated temperature increase, the most conservative (+ 2 °C) and most drastic (+ 4 °C) scenarios predict an increase of approximately 6.5 and 15%, respectively, in the concentrations of PM$_{2.5}$ and PM$_{10}$, with a progressive increase in deaths attributed to air pollution. The study shows that the increase in temperature will have impacts on air particulate matter and health outcomes. Climate change mitigation and pollution control policies must be implemented for meeting new WHO air quality standards which may have health benefits.

Keywords Recife · Air quality · Air pollutants · Temperature · Health impact assessment

Introduction

Air pollution is composed of a complex mixture of gaseous and particulate components, each of them has an adverse effect on human and environmental health. Although the air pollution components vary between different regions of the world, studies consistently show that air pollution is an important modifiable risk factor that significantly increases morbidity and mortality of various health conditions (Dominski et al., 2021). Among the air pollutants, particulate matter (PM) has received special attention, as it is a pollutant that has been proven to be dangerous to human health (Han et al., 2021).
The particulate material is classified according to its diameter into coarse (PM$_{10}$) and fine (PM$_{2.5}$) particulate matter. PM$_{10}$ is generated by activities such as construction and dust resuspension by traffic, typically mechanical processes, whereas PM$_{2.5}$ generally originates from combustion sources. These pollutants enter the human body through the airway and contribute to the emergence of important adverse health events (Li et al., 2022). A number of studies have demonstrated the extent of these adverse effects, including ischemic heart disease and several respiratory diseases (Dominski et al., 2021, Yang et al., 2022a, 2022b), stroke (Wu et al., 2022), respiratory and cardiovascular hospital admissions and cancer (Maciel et al., 2019; Yang et al., 2022a, 2022b).

In 2006, the World Health Organization (WHO) established safety limits for particulate matter in the atmosphere: 10 µg/m$^3$ of annual average and 24-hour average of 25 µg/m$^3$ for PM$_{2.5}$, and annual average of 20 µg/m$^3$ and 24-hour average of 50 µg/m$^3$ for PM$_{10}$ (WHO 2006). However, in 2021, WHO updated the reference values for several pollutants, including PM$_{10}$ and PM$_{2.5}$. According to the most recent recommendation, the maximum annual level of PM$_{2.5}$ and PM$_{10}$ should be 5 µg/m$^3$ and 15 µg/m$^3$, respectively (WHO, 2021).

In addition to the direct influence of emission sources, air pollution is closely associated with meteorological conditions and, therefore, climate change has an impact on the concentration of air pollutants (Ingole et al., 2022). Changes in climate are capable of affecting parameters such as precipitation, atmospheric circulation, temperature, incidence of radiation and ventilation, with particulate matter and ozone being the pollutants most sensitive to climate changes (Kinney 2021). One study conducted in the UK showed an association between seasonal heat waves and periods of highest pollution, and hottest days coinciding with the highest peaks of particulate matter in the atmosphere (Kalisa et al., 2018). In addition, other studies showed the association between temperature extremes and increased mortality (Hu et al., 2022). Marked changes in temperature are known to cause physiological stress and alter a person’s normal response to toxic agents (Verheyen et al., 2022).

Worldwide, sensitivity to climate change-related events depends on location. Recife, capital of the state of Pernambuco, Brazil, has been identified as the 16th most vulnerable city in the world to climate change, due to its geographic characteristics and occupational processes (IPCC 2014, Recife 2021). The city is located in the Northeast region of Brazil, occupying an area of about 218 km$^2$, being the ninth most populous Brazilian city, with approximately 1,661,017 inhabitants (IBGE, 2021). Although Recife is not a city with critical episodes of air pollution, several studies showed average PM$_{2.5}$ levels above the new WHO recommendations (Andrade et al., 2012, Leão et al., 2021), and vulnerability related to climate change reinforces the need for studies to predict the combined health effects of air pollution and climate change. A previous study (Leão et al., 2021), showed positive impacts of the lockdown in Recife on air pollutants and consequently on health indicators, using the Health Impact Assessment methodology proposed by the WHO. The authors stated that, in a scenario of reduction in air pollution to levels equivalent to those measured during the lockdown, it would be sufficient to increase the population’s life expectancy by 0.7 years. In view of the importance of this methodology and findings, the present study aimed to assess the health benefits related to controlling PM$_{10}$ and PM$_{2.5}$ levels to new limits proposed by the WHO in 2021, and to estimate the impacts related to climate change in Recife, Brazil, from two future scenarios (2°C increase and 4°C increase in daily average temperature).

Material and methods

Study setting

The city of Recife has an area of approximately 217 km$^2$ and more than one million six hundred and sixty thousand inhabitants (Prefeitura do Recife, 2016; IBGE, 2021). The city’s predominant climate is humid tropical, with high temperatures and rainfall from winter to autumn. Regarding the relative humidity of the air, the annual historical average is 80%. The average temperature is 25.5 °C (Do Nascimento Silva, 2019).

Recife is located in the coastal area of the state of Pernambuco, Northeast Brazil (Fig. 1), with an altitude between 2 and 10 meters above sea level, intersected by several rivers, streams and mangroves, and is highly sensitive to tidal movements (De Paiva, 2014). For over 25 years, scientists have
pointed out the danger that rising sea levels pose to the entire region, as the city has always suffered from problems of urban drainage and salinization of its aquifers, since it is located on an immense plain flooded with mangroves. Predicted impacts include beach erosion, verticalization and reduction in sandbanks, worsening water and sewage runoff and encroachment on lower regions (Neves & Nuehe, 1995).

According to the Pernambuco State Transit Department (DETRAN-PE 2018), the vehicular fleet in Recife reached 692,866 vehicles in July 2018, of which 408,249 were cars. It should be noted that in the last 10 years the city’s fleet grew by 53%, with more than 240 thousand new vehicles on the streets (Do Nascimento Silva, 2019).

Environmental data

The concentrations of PM$_{10}$ and PM$_{2.5}$ refer to daily data between January 1, 2021, and November 7, 2021, equivalent to more than 85% of measurements for one year (above 75% required for the Health Impact Assessment). Data were extracted from the European Center for Medium-Range Weather Forecasts (ECMWF) “Copernicus Atmospheric Monitoring Service” with procedures similar to Da Silva Júnior et al., (2020) and Carvalho et al., (2021).

Population and health data

Population, mortality and hospital admission data were collected from the database of the Brazilian Unified Health System (DATASUS) using the year 2019 (Brasil 2021). The Data from 2020 and 2021 were avoided due to the impact of the COVID-19 Pandemic on rates of mortality and hospital admissions due to respiratory problems, in addition to the probable underreporting of the records.

For short-term effects (related to exposure to PM$_{10}$), in addition to population data (total and by age group), total non-external causes mortality (A00-R99) (all ages), cardiac hospital admissions (I00-I52) (all ages), respiratory hospital admissions (J00-J99) (all ages, 15-64 years and 65 years and over) were extracted. For long-term effects (related to exposure to PM$_{2.5}$), population data (ranges from age 30 to 85 years or more), total mortality (A00-Y98) and cardiovascular mortality were extracted (I00-I99) using the same population age ranges.

Deaths attributed to air pollution

The estimation of deaths attributed to exposure to PM$_{10}$ (total non-external causes mortality) and to PM$_{2.5}$ (total mortality) was performed according to Ostro et al., (2004). The annual mean value (2021) of PM$_{10}$ and PM$_{2.5}$ and baseline values of 10 µg/m$^3$ for
PM$_{10}$ (Ostro et al., 2004) and 5 µg/m$^3$ to PM$_{2.5}$ (WHO 2021) were used. The values were obtained based on the equations below:

$$RR = \exp[\beta (X - X_0)]$$  \hspace{1cm} (1)

$$N_{\text{assigned}} = \frac{(RR - 1)/RR}{\beta} \times N_{\text{total}}$$ \hspace{1cm} (2)

Where $RR = \text{Relative risk}$, $X = \text{average annual concentration of PM$_{2.5}$ or PM$_{10}$ (total mortality)}$, $X_0 = \text{basal concentration of PM$_{2.5}$ or PM$_{10}$}$, $\beta = \text{concentration response function coefficient} = 0.0008$, $N_{\text{assigned}} = \text{number of total deaths assigned to PM$_{2.5}$ or PM$_{10}$}$, respectively, $N_{\text{total}} = \text{total number of total deaths}$.

Health impact assessment

The Health Impact Assessment was conducted according to the methodology proposed by Pascal et al., (2013) simulating the scenario in which the annual average of PM$_{10}$ and PM$_{2.5}$ in Recife were equivalent to the new limits proposed by the WHO in 2021 (15 µg/m$^3$ for PM$_{10}$ and 5 µg/m$^3$ for PM$_{2.5}$).

To assess the health benefits arising from the scenario of reduced PM$_{10}$ levels (short term exposure), the equation below was used:

$$\Delta y = y_0(1 - e^{-\beta \Delta x})$$ \hspace{1cm} (3)

Where $\Delta y = \text{health benefits associated with decrease in concentrations of PM10, in annual number of deaths or hospitalizations}$, $y_0 = \text{baseline health outcome, in annual number of deaths or hospitalizations}$, $\beta = \text{concentration response function coefficient, } \Delta x = \text{decrease in the concentration of the pollutant in a given scenario, in } \mu g/m^3$.

With regard to the health benefits associated with reducing annual PM$_{2.5}$ levels, we conducted based on the standard summary life table methodology, as described by Pascal et al., (2013) calculated from the equation below:

$$\eta D_{\text{m impacted}} = \eta D_{\text{x}} e^{\beta \Delta x}$$ \hspace{1cm} (4)

Where $\eta D_{\text{m}} = \text{total number of deaths in the age group starting at age "n" for "m" years}$, $\eta D_{\text{x}} = \text{number of deaths over a 5-year interval (starting at the age of 30 to the class of 85 or older)}$.

Based on these results, the gain in life expectancy of this population was calculated. All calculations were performed in the Microsoft Excel® spreadsheet developed by the Aphekom project, available at http://aphek om.net/aphek om/ All detailed equations are provided in these tools.

Economic cost for hospital admissions and mortality

The economic evaluation of expenses for hospitalizations due to respiratory and cardiac problems were calculated based on the average cost per day and the average hospital stay (Abe & Miraglia 2016). Data on hospitalization costs and average number of hospitalization days in Recife were obtained through the DATASUS database, referring to the year 2019.

The morbidity assessment was estimated according to equation below:

$$Ch = V_i \times N_d \times N_c$$ \hspace{1cm} (5)

Where $Ch = \text{Cost of hospitalization, } V_i = \text{unit value of a daily admission, } N_d = \text{average number of days of hospitalization due to a certain disease, } N_c = \text{number of cases due to a specific disease}$.

Economic assessment of mortality $> 30$ years

The evaluation of economic costs associated with mortality for $> 30$ years was estimated according to Corá et al., (2020) using equation below:

$$C_{m} = V_d \times V_{SL}$$ \hspace{1cm} (6)

Where $C_{m} = \text{health cost of mortality for people over 30 years old, } V_d = \text{deaths associated with air pollution}$, $V_{SL} = \text{value of a statistical life, attributed to Bickel and Friedrich (2005) a value of } € 1,000,000 \text{ and converted into reais. The following conversion was considered: 1 euro is equivalent to 6.44 Brazilian reais, 1 euro is equivalent to 1.15 US Dollars and 1 US Dollars is equivalent to 5.75 Brazilian reais}$.

Scenarios with increased temperature

The simulation of PM$_{10}$ and PM$_{2.5}$ levels based on the temperature rise was carried out with four scenarios, two more conservative (+ 2 °C) and two more alarmist (+ 4 °C), both within the ranges contemplated in the new document of the IPCC (IPCC 2021) (Table 1).

The estimated values were calculated using machine learning using two different approaches for each of the pollutants: in the first approach, the estimated concentrations were calculated based only on...
the increase in temperature (+2°C or +4°C), while the second approach incorporated changes in the other meteorological variables (humidity, pressure, wind speed, precipitation and solar radiation index) when the temperature was increased by +2°C or +4°C.

The model used was Support Vector Machine. The continuous dependent variable was the concentration of the pollutant (PM$_{10}$ or PM$_{2.5}$) and the predictor variables were temperature (Scenarios 1 and 3) or temperature and meteorological variables (Scenarios 2 and 4). The training sample (observed or actual values) consisted of observed data from the study period, while the test sample (expected values) included increased temperature values (+2 or +4°C) (Scenario 1 and 3) or temperature values increased in addition to the meteorological variables affected by the temperature increase.

To this end, the behavior of each meteorological variable related to the increase in temperature was estimated in isolation using machine learning. Afterward, the estimated values of each meteorological variable were combined with the temperature increase (2 or 4°C) to estimate the changes in the concentrations of PM$_{10}$ and PM$_{2.5}$ (Table 1).

The estimated percentage increase in the averages of PM$_{10}$ and PM$_{2.5}$ was calculated in relation to the observed values. To estimate the impact on deaths attributable to air pollution, the pollutant averages estimated by the increase in temperature (combined or not with the meteorological variables) were used for the calculation using Eqs. 1 and 2.

### Results

The mean annual concentration, standard deviation and 5th and 95th percentile data for PM$_{10}$ and PM$_{2.5}$ in the city of Recife are described in Table 2. These average values were used for estimation of deaths attributable to air pollution, for calculation of health benefits in a scenario in which the averages reduced to the new WHO limits, and for calculation of scenarios with a temperature increase.

Table 3 shows the number of deaths and hospital admissions, as well as the number and percentage of deaths attributable to air pollution in Recife. Considering the impact of exposure to PM$_{10}$ on total mortality, the estimated number of deaths for all ages is 85, equivalent to 0.79% of all deaths. In the case of the relationship between PM$_{2.5}$ and total mortality for over 30 years, the number of deaths attributable to this pollutant is 60 deaths, which is equivalent to 0.56% of all deaths among those over 30 years of age.

Reducing the levels of air pollutants to the new WHO limits is able to reduce 136.5 deaths in the case of total mortality among people over 30 years old, 78 deaths in the case of cardiovascular mortality (related to the reduction in PM$_{2.5}$) and 30.9 deaths due to total non-external causes (related to PM$_{10}$ reduction). In terms of benefits in hospital admissions, the gain is a reduction in more than 50 and 30 admissions for respiratory and heart problems, respectively. The gain in the average life expectancy of the population of Recife reaches 15.2 months, while the monetary gains (avoided cost) would exceed $150 million, when

### Table 1: Summary of simulated scenarios of temperature rise

| Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|------------|------------|------------|------------|
| Pollutants | PM$_{10}$ and PM$_{2.5}$ | PM$_{10}$ and PM$_{2.5}$ | PM$_{10}$ and PM$_{2.5}$ |
| Temperature increase (°C) | +2 | +2 | +4 | +4 |
| Inclusion of meteorological variables | NO | YES | NO | YES |

### Table 2: Annual mean concentration (± standard deviation) of PM$_{10}$ and PM$_{2.5}$ in Recife, Brazil (year 2021)

| Pollutant | Daily mean (μg/m$^3$) | Standard deviation (μg/m$^3$) | 5$^{th}$ percentile (μg/m$^3$) | 95$^{th}$ percentile (μg/m$^3$) |
|-----------|------------------------|-------------------------------|-------------------------------|-------------------------------|
| PM$_{2.5}$ (daily average) | 11.71 | 2.48 | 7.68 | 15.65 |
| PM$_{10}$ (daily average) | 20.05 | 4.69 | 12.19 | 27.30 |
considering the reduction in total mortality among people over 30 years of age (Table 4).

Data related to the behavior of PM$_{10}$ and PM$_{2.5}$ in scenarios with temperature rise (+2°C and +4°C) alone and combined with predicted changes in meteorological parameters are summarized in Table 5. Scenarios that consider the combined temperature rise and the meteorological parameters (associated with the increase in temperature) have a greater impact on the increase in air pollutants (PM$_{10}$ and PM$_{2.5}$) both in the 2°C rise and the 4°C rise scenario. In the most critical scenario (+4°C C, combined with meteorological parameters) the increase in PM$_{2.5}$ levels reaches 14.4% and in PM$_{10}$ levels reaches 15.8%. In this same scenario, deaths

Table 3 Annual means of respiratory and cardiac hospitalizations and total, non-external causes and cardiac mortality in 2019 in Recife, Brazil

| Health outcome                     | ICD10  | Age      | Annual mean | Deaths attributed to air pollution | Percentage of deaths attributed to air pollution | Annual mean number per 100,000 |
|------------------------------------|--------|----------|-------------|-----------------------------------|-----------------------------------------------|-------------------------------|
| Total mortality                    | A00-Y98| > 30     | 10,683      | 60 (PM$_{2.5}$) + 85 (PM$_{10}$)  | 0.79*                                          | 1107                          |
| Cardiovascular mortality           | I00-I99| > 30     | 3,198       | –                                 | –                                             | 331                           |
| Cardiac hospitalizations           | I00-I52| All      | 11,404      | –                                 | –                                             | 693                           |
| Respiratory hospitalizations       | J00-J99| 15-64    | 2,067       | –                                 | –                                             | 126                           |
| Respiratory hospitalizations       | J00-J99| >65      | 2,275       | –                                 | –                                             | 138                           |
| Respiratory hospitalizations       | J00-J99| All      | 8,801       | –                                 | –                                             | 535                           |

*This information refers to deaths attributed to PM$_{10}$ (higher %)

Table 4 Potential health and economic benefits of reducing daily PM$_{10}$ and PM$_{2.5}$ levels on hospitalizations, mortalities and life expectancy, in Recife, Brazil

|                  | Annual number of deaths avoided | Annual number of deaths avoided per 100,000 | Gain in life expectancy | Life Years gain | Avoided economic cost US$ Millions |
|------------------|---------------------------------|---------------------------------------------|-------------------------|-----------------|-----------------------------------|
| **Decrease to 5 µg/m$^3$ in PM$_{2.5}$ levels** |                                 |                                             |                        |                 |                                   |
| Total mortality  | 136.5                           | 14.1                                        | 15.2                    | 34092.3         | 157.9                             |
| Total cardiovascular mortality | 78.0                           | 8.1                                         | –                      | –               | 90.2                              |
| **Decrease to 15 µg/m$^3$ in PM$_{10}$ levels** |                                 |                                             |                        |                 |                                   |
| Total non-external mortality | 30.9                           | 1.88                                        | –                      | –               | 35.7                              |
| Respiratory hospitalizations   | 50.2                           | 3.05                                        | –                      | –               | 0.016                             |
| Cardiac hospitalizations       | 34.4                           | 2.09                                        | –                      | –               | 0.017                             |

Table 5 Mean concentration of PM$_{2.5}$ and PM$_{10}$ (µg/m$^3$) and simulated temperature increase scenarios (+2 °C and +4 °C) considering the isolated increase in temperature (only T) and all meteorological variables (all variables)

|                  | PM$_{2.5}$ | % variation | Deaths related to air pollution | PM$_{10}$ | % variation | Deaths related to air pollution |
|------------------|------------|-------------|---------------------------------|-----------|-------------|---------------------------------|
| Mean (2021)      | 11.71      | –           | 60                              | 20.05     | –           | 82                              |
| Scenario 1       | 12.47      | 6.5         | 64                              | 21.32     | 6.4         | 96                              |
| Scenario 2       | 12.61      | 7.7         | 65                              | 21.55     | 7.5         | 98                              |
| Scenario 3       | 13.25      | 13.2        | 70                              | 22.84     | 13.9        | 109                             |
| Scenario 4       | 13.40      | 14.4        | 72                              | 23.23     | 15.8        | 112                             |
attributed to air pollutants reach 72 deaths related to PM$_{2.5}$ and 112 deaths related to PM$_{10}$.

Discussion

This study shows the averages of PM$_{2.5}$ and PM$_{10}$ above the WHO limits in Recife, a Brazilian metropolis. When we simulate the scenario of reducing the concentrations of these pollutants below the new WHO limits, this would avoid more than 130 deaths and 84 hospitalizations for respiratory or cardiovascular problems. These benefits represent a 15.2 month gain in life expectancy and a gain of nearly $160$ million. Regarding the simulated temperature increase, even the most conservative scenario (+ 2 °C), it predicts an increase in PM$_{2.5}$ and PM$_{10}$ concentrations and this increase is even greater in the more drastic scenario (+ 4 °C). These conditions consequently increase the deaths attributed to air pollution.

Particulate matter is considered an efficient indicator of the relationship between air quality and harmful health effects (Kim et al., 2015). Results from numerous epidemiological studies point to an increased risk of death for respiratory and cardiovascular causes related to air pollution (Atkinson et al., 2014), in both children and adults (Dominski et al., 2021). These findings are supported by studies with a large number of subjects (Pun et al., 2017, Hayes et al., 2020). Furthermore, the number of deaths attributable to exposure to PM$_{2.5}$ increased from 3.5 to 4.2 million cases from 1990 to 2015 (Cohen et al., 2017).

Despite the negative outcomes related to air pollution, especially particulate matter, measures adopted by governments around the world have been shown to be effective in reducing the levels of air pollutants and, consequently, improving health indicators. It is known that positive responses in respiratory outcomes appear within a few weeks after a reduction in pollution levels, and followed by improvement of other associated indicators, such as social and economic ones (Schraufnagel et al., 2019).

A case study conducted in North Carolina analyzed the concentrations of SO$_2$ and sulfate in PM$_{2.5}$ between the years 2002 and 2012 in order to assess the impacts of the NC Clean Smokestacks Act of 2002, a state law that required greater pollution reductions than those defined by federal law. The monitoring carried out showed a downward trend in the levels of SO$_2$ (−20.3% per year) and sulfate associated with PM$_{2.5}$ (−8.7% per year) and estimated a 63% reduction in premature deaths in 2012 (Li & Gibson 2014).

In China, a study based on satellite data, aimed to evaluate the effects of air pollution control policies on improvement of PM$_{2.5}$ pollution, after the implementation of the 11th Five-Year Plan (FYP) and later two other strict air pollution policies to pollutant emission control (the 12th FYP on Air Pollution Prevention and Control in Key Regions (APPC-KR) in 2012, and the Action Plan of Air Pollution Prevention and Control (APPC-AP) in 2013). The results showed that although China still has a heterogeneous distribution of air pollution, the adoption of these policies was effective in promoting improvements in air quality (Ma et al., 2019).

In addition to local or national policies, other programmed or unplanned interventions have shown a positive impact on the reduction in air pollutants. The recent example of the implementation of lockdown for reducing the transmission of Sars-Cov-2 proved to be an efficient measure to reduce the levels of air pollutants in several parts of the world (Venter et al., 2020), including in Recife (Leão et al., 2021). Other events that have been proven to affect air pollution include the truck Driver’s strike (Chiquetto et al., 2021), general strike (Fransen et al., 2013) and even the Olympic Games (Li et al., 2010), and are often associated with improved health indicators.

These health benefits also have repercussions from an economic point of view, given that hospital admissions generate high costs for health systems. For example, in 2012 alone, 1.1 million hospitalizations for cardiovascular diseases cost R$ 2.3 billion in Brazil (Brazil, 2014), corresponding to about 0.7% of the national GDP (Siqueira et al., 2017). Recent data (from January to October 2021) show that the expenses related to hospitalizations for respiratory and cardiovascular diseases in Brazil cost around R$ 3.294 billion (Brazil, 2021). The state of Pernambuco pays more than R$ 142.025 million for these same expenses, and the number of deaths related to these diseases exceeds 5,640 cases in the same period (Brazil, 2021).

In addition to the problems mentioned above, Recife (as well as other large cities located in developing countries) suffers from numerous other social and environmental problems, such as water use (Petelet-Giraud et al., 2018), land occupation and
poverty (Arruda 2021). The development of the city of Recife is linked to major environmental changes in the region’s natural plains, and changes in the complex landscape made up of mangroves, restingas, deltas and reefs. These changes culminated in the city’s current urban environment. The population increase experienced in the city from the mid-twentieth century promoted a series of structural changes, such as the expansion of social inequalities, socio-environmental degradation and the deterioration of survival conditions of people located in the region (de Almeida & Barros Corrêa, 2012).

The metropolitan region of Recife is marked by a large number of irregular households and, therefore, a large part of the population has inadequate housing (Brasil, 2008). In 2005, the city had 41% of the houses located in slums, two thirds of the population lived in poverty and 21 thousand houses did not have any sanitary facilities (Saule Júnior & Cardoso, 2005). Some reports have already shown that a large part of the city’s sewage is not properly treated (Novaes, 2018). Recife is known as the capital of palafitas (riverside dwellings supported by wood), and in 2004, 7000 families (about 30,000 people) lived in these buildings (Bitoun, 2004).

Returning to the environmental issue in the city, the main sources of atmospheric pollutants are related to emissions from oceanic ships, industries installed in the region and the intense flow of vehicles (De Miranda et al., 2012). This situation is responsible for PM$_{10}$ and PM$_{2.5}$ levels above the new WHO recommendations (Andrade et al., 2012, Léao et al., 2021). Although these concentrations are not as high as in other cities around the world, the city’s vulnerability to climate change underlines the need for a more careful look at Recife, as these two topics (air pollution and climate change) have close association.

The relationship and impact of climate change on air pollution has received attention in some parts of the world. A Chinese study based on the simulation of air pollution reduction and climate change mitigation in three regions of China, considering the policies in force at the time, covering the period from 2005 to 2030. The results show a heterogeneity in the behavior of pollutants, and the authors conclude that governments must establish a range of constraints and framework improvements to achieve environmental sustainability (Zheng et al., 2016).

In a more specific scenario simulating a 4.5°C temperature increase, Huang et al., (2021) revealed a national reduction in PM$_{2.5}$ levels, but an increase in some regions of China. Even with reduced PM$_{2.5}$ levels, the effect of rising temperatures is likely to exacerbate negative health impacts, including COPD, ischemic heart disease, stroke and lung cancer, but these adverse impacts would be mitigated when considering pollutant emission control scenarios. Another study projecting future climate changes (2046-2055) and impacts on air pollution, notably for O$_3$ and PM$_{2.5}$, in Southeast Asia, revealed a scenario of a warmer and wetter atmosphere, with higher precipitation and winds stagnation. Two scenarios were simulated (RCP4.5 and RCP8.5) and the behavior of the pollutants was different between them. In the first case, reductions in O$_3$ and PM$_{2.5}$ levels are expected, while the most drastic scenario shows an increase of up to 4.2% in annual PM$_{2.5}$ levels (Nguyen et al., 2019). This increase, considered drastic by the authors, is lower than the more conservative scenario simulated in the present study (increase of 2 °C).

The study by Tagaris et al., (2009) simulated the trend of PM$_{2.5}$ and O$_3$ concentrations in 2050, considering the variation of weather conditions due to climate change and a heterogeneity of pollutant levels reported in different regions of the USA. PM$_{2.5}$ levels appear to be slightly increased only in the northern part of the country, but still with negative health effects. Finally, the authors point out that concerns about the increase in PM$_{2.5}$ should be greater than with variations in O$_3$, because premature mortality is about 15 times higher than that due to O$_3$. Taking into account the results of these studies, we emphasize the concern about the levels of PM$_{10}$ and PM$_{2.5}$ in Recife in the face of temperature increases. Our data showed an approximately 15% increase in air pollutant levels, and an increase of up to 20% in deaths related to PM$_{2.5}$ and up to 36% in deaths attributed to PM$_{10}$.

Even in realistic scenarios, temperature has proven to influence the relationship between air pollutants and hospital admissions for cardiovascular disease (Lokotola et al., 2020), asthma (Ueda et al., 2010), acute exacerbation of COPD (Chen et al., 2019) and mental and behavioral disorders (Da Silva et al., 2020). The combination of these two components (climate changes and air pollution) becomes more complex in environmentally vulnerable regions (extreme temperatures, susceptible to flooding, fires).
and Recife is part of this context. In this case, cascading, nonlinear, and interactive health effects are expected, given the complexity of this scenario (Kinney 2018).

Although the present study has limitations regarding available environmental data (only a single year) and health data (available by the government and likely underreported), the study reinforces the need for special attention to Recife, not just because it is a city vulnerable to flooding associated with climate change, but due to the likely increase in the levels of air pollutants associated with the increase in temperature, not only in the scenario with an isolated increase in temperature, but mainly in the scenario in which the behavior of meteorological variables was combined to the increase in temperature. It is noteworthy that even in the most conservative scenario, the increase in deaths attributable to PM2.5 and PM10 is greater than 6%. On the other hand, the study points out that public policies aimed at reducing levels of pollutants in order to reach the new WHO standards can bring health and economic benefits.

Air pollution remains a major challenge for public administrators in urban areas, with a close relationship with human activities, such as transport and human mobility (Angelevska et al., 2021), and prediction models and data interpretation are important allies for facing this challenge (Gibergans-Baguena et al., 2020, Thangjai et al., 2022). In the present study, we used machine learning to predict the behavior of air pollutants in scenarios of increased temperature and this model has already been used in several studies of air quality (Cole et al., 2020, Hu et al., 2021).

Conclusion

Air pollution is one of the great challenges in public health and the new limits proposed by the WHO for air pollution aim to reduce health risks. The present study showed that by adopting (and reaching) the proposed new limits for PM10 and PM2.5 recommended by WHO a total of more than 136 deaths would be avoided in the city of Recife, Brazil. This would result in an increase in population life expectancy by 15.2 months. Furthermore, reducing pollutant levels would also reduce over 80 hospitalizations for respiratory and cardiovascular problems per year. These health benefits would be enough to reduce monetary costs in excess of 150 million dollars.

In addition, the scenario simulating temperature increase showed an increase in the concentrations of PM10 and PM2.5 and consequently the number of deaths attributed to air pollution. These results were obtained even in the most conservative scenario (increase of 2 °C). When, in addition to the isolated increase in temperature, the simulation was conducted by changing the meteorological variables as a function of the increase in temperature, the levels of pollutants increased even more. These findings reveal that the increase in temperature will be a major challenge to reduce the levels of air pollutants. Public administrators and policy makers need to be aware of the scenarios presented in this study, and to develop and implement the effective air pollution control policies. In these conditions, the impacts of air pollution on health indicators can be minimized.

Authors’ contributions MLPL was responsible for the first version of the manuscript, LZ was responsible for text revision and data discussion, FMRSJ was responsible for information collection and data analysis and was the study supervisor.

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Data Availability The datasets used and/or analyzed during the current discussion are available and from the corresponding author upon reasonable request.

Declarations

Conflicts of interest The authors declare no conflicts of interest

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

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