



A better understanding of air quality resulting from the effects of the 2020 pandemic in a city in the equatorial region (Fortaleza, Brazil)

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Abstract

The year 2020 was atypical due to the pandemic caused by the SARS-CoV-2 virus (COVID-19), providing a unique opportunity to understand changes in air quality due to the reduction in urban activity. Therefore, the aim of the present study was to perform an integrated evaluation on the influence of the effects of the 2020 pandemic on air quality in the city of Fortaleza, investigating levels of PM_{2.5}, PM₁₀, NO₂, NO, SO₂, CO, and O₃, corresponding health risks, as well as the influence of meteorological variables and urban activity. In all phases analyzed, significant reductions were found in NO_x, NO, NO₂, and CO. A considerable reduction in PM_{2.5} and PM₁₀ was found in the early phases, with an increase in the later phases. These findings are explained by the nearly 50% reduction in vehicular traffic and the consequent reduction in fossil fuel emissions, mainly in the partial lockdown and total lockdown periods, as well as reductions in commercial (stores/shops) and industrial activities. The variation in O₃ was initially non-significant, followed by a considerable increase in the last three phases analyzed; this increase was influenced by changes in temperature and the incidence of sunlight. SO₂ concentrations increased in the period studied, demonstrating that the vehicular fleet, local commerce, and other activities are not the predominant sources of this compound. Estimated health risks were reduced by half during the lockdown period, especially for non-smokers, followed by a drastic increase in the last three phases. The planetary boundary layer was positively correlated with O₃ and PM₁₀ and negatively correlated with NO_x, NO₂, and NO, indicating its influence on the distribution of pollutants in the lower atmosphere and, consequently, air quality.

Keywords SARS-CoV 2 · Lockdown · Air quality · Cancer risk · Meteorology · Integrated analyses

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Introduction

The year 2020 was atypical due to the pandemic caused by the SARS-CoV-2 virus (COVID-19) declared by the World Health Organization on March 11th of the same year (WHO 2020). This scenario brought about radical changes in the functioning of cities and the daily lives of populations. Non-essential activities were suspended, and social distancing became necessary. In Brazil, the cities of São Paulo, Rio de Janeiro, and Fortaleza were the first with a considerable increase in the number of cases of infection as well as the first records of deaths from COVID-19 and were the first cities to adopt social distancing (BRASIL 2020). Lockdown periods determined through legislative measures directly influenced the movement of people on the streets and, consequently, the presence of traffic in neighborhoods.

In Fortaleza, the initial partial lockdown (PL) period was from March 17th to May 7th, 2020, when some activities were suspended (DECREE N°33.519—DOE 2020a). This was followed by a stricter period—denominated total lockdown (TL)—from May 8th to 31st, 2020, when nearly all productive activities were suspended and movement was limited (DECREE N°33.575—DOE 2020b). After these two periods, restrictions were lessened. Businesses began to return to their activities in the transition phase (TPh) from June 1st to 7th and subsequent economic recovery phases: phase 1 (Ph1) from June 8th to 21st, phase 2 (Ph2) from June 22nd to July 5th, phase 3 (Ph3) from July 6th to 19th, and phase 4 (Ph4) from July 20th to November 30th (DECREE N°33.608—DOE 2020c).

Social distancing measures during the pandemic have led to changes in the air quality of cities throughout the world, enabling the in situ investigation of dynamics that was previously only possible through atmospheric models (Finlayson-Pitts and Pitts 2000; Peralta et al. 2019). This exceptional time offers a unique opportunity for the evaluation of human activities that exert an impact on the environment as well as an understanding of the dynamics of atmospheric pollutants.

Therefore, the aim of the present study was to evaluate the influence of the 2020 pandemic on air quality in the city of Fortaleza, which is located on the semiarid tropical region of Brazil, where the solar intensity is greater and must have a different effect compared to regions at middle and high latitudes. For such, we performed an integrated evaluation of (1) levels of PM_{2.5}, PM₁₀, NO₂, NO, SO₂, CO, and O₃ in 2020 and their dispersion, (2) the influence of meteorological variables, including the variation in the planetary boundary layer (PBL), (3) the influence of main urban activities, such as vehicular traffic, and (4) health risks.

These data will be useful, as studies on air quality and associated variables in equatorial areas are scarce. Moreover, this is a time at which sources of pollution are practically halted, offering a unique opportunity to understand what air

quality variables exert an influence on the health of people living in urban areas (Rocha et al. 2020).

Materials and methods

Study area

The city of Fortaleza is located on the Atlantic coast in the northeastern region of Brazil and has an area of approximately 314.93 km², with a population of more than 2.5 million residents (IBGE 2019)(Fig. 1). The region has two well-defined seasons (a dry season from August to December and a wet season from January to July). Mean temperature ranges from 25 to 28 °C. Annual mean wind velocity is 3.5 m s⁻¹, and annual mean rainfall is 1600 mm, with rains concentrated between February and May (Sousa et al. 2015; Gusev et al. 2004; Rocha et al. 2016).

In April 2020, the city reached the mark of 1,142,821 vehicles, approximately 37.4% of which use gasoline, 2.9% are fueled by hydrated ethanol, and 8.2% are powered by diesel. Flexible-fuel (gasoline or ethanol) vehicles represent approximately 45.8% of the total fleet, and their number is rapidly increasing (DENATRAN-CE 2020). Besides vehicular emissions, the following human activities are performed in the area: port, petrochemical, and food industries in the eastern portion of the city; industrial center in the southern portion; and port and industrial area in the western portion. Offshore oil extraction activities also occur in the area (Fig. 1).

Data sources

Data on the following compounds were obtained at 1-h intervals from automatic monitoring stations: ozone (O₃; Serinus® 10 model), carbon monoxide (CO; Serinus® 30 model), nitrogen dioxide (NO_x; Serinus® 40 model), sulfur dioxide (SO₂; Serinus® 50 model), and particulate matter (PM_{2.5}/PM₁₀; Spirant BAM). Meteorological variables (temperature, relative humidity, solar radiation, speed, and wind direction) were also determined at the monitoring stations.

Cancer risk

The risk to human health was estimated using the chronic daily intake (CDI) (mg kg⁻¹ day⁻¹) per lifetime model (Eq. 1) considering the variables listed in Table 1.

$$CDI = \frac{(CA.IR.ED.EF.L)}{(BW.ATL.NY)} \quad (1)$$

The risk of cancer was estimated by multiplying the CDI by the relative risk (RR)(Eq. 2) according to the US EPA (1992;

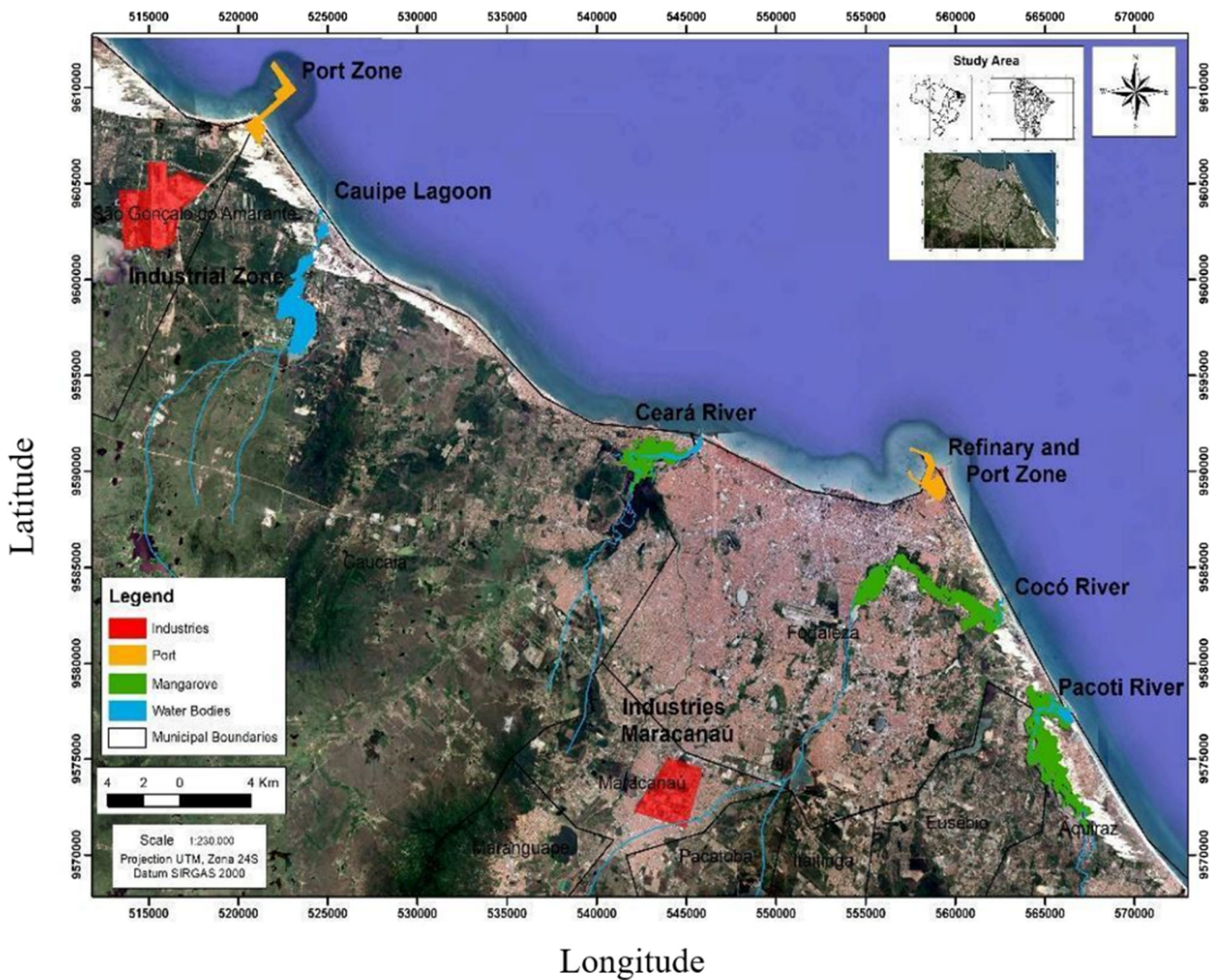


Fig. 1 Study area

Table 1 Variables used in exposure calculations and estimate of cancer risk

Parameter	Description	Value	Unity
CA	Concentration	-	mg.m ⁻³
IR	Inhalation Rate (adult)	1.02	m ³ .h ⁻¹
ED	Exposure Duration	7 ^a	hour.week ⁻¹
EF	Exposure Frequency	52	week.year ⁻¹
L	Exposure Time	35 ^b	Year
BW	Body Weight Man/Woman	70/60	Kg
ATL	Life Expectancy Man/Woman	72/79 ^c	Year
NY	Number of Days in Year	365	d.year ⁻¹

^a Considering that an individual is exposed for one hour per day on these avenues

^b Considering that an individual frequents these avenues for a maximum of 35 year of life

^c IBGE (2014)

1996) and a study conducted by Hamra et al. (2014). In the present investigation, we used RR values for all types of people (1.09—general risk), for those who smoked for many years (1.44—ex-smokers), and for those who never smoked (1.18—non-smokers).

$$CR = CDI.RR \tag{2}$$

Planetary boundary layer

The planetary boundary layer (PBL) is the physical interface between the atmosphere and surface of the planet and is therefore directly influenced by dynamic and thermodynamic processes occurring on the surface on a time scale of less than 1 h and a spatial scale of less than 1 km. The PBL is the part of the terrestrial atmosphere and contains the air that people breathe. It is also where the dispersion of air pollutants occurs, depending on weather conditions (Stewart 1979; Cao et al. 2020). In

the present study, the maximum boundary layer height (PBL_{max}) over the city of Fortaleza and its association with air quality were investigated.

Boundary layer height was obtained from a reanalysis of hourly ERA5 data (UTC time) on single levels (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form>) covering the diurnal cycle. The data were in a regular $0.25^\circ \times 0.25^\circ$ grid, and the period analyzed was February 1st to November 30th, 2020. A subset with 8040 points (Time) centered on the city of Fortaleza (longitude 38.5° W and latitude 3.8° S) was generated. According to the site, the boundary layer height is calculated based on the bulk Richardson number. Further information on this method can be found in Voegele and Holtslag (1996), Richardson et al. (2013), Chandra et al. (2014), and Cao et al. (2020).

Trajectory model analysis

Trajectories of pollutants modeled using the HYSPLIT method enable estimating the dispersion of pollutants and the vertical height reached in the atmosphere. Trajectories with a geographical origin at latitude (UTM) 9587580.04 and longitude (UTM) 552066.322 (central region of the Fortaleza) were determined considering the backward trajectory of the air mass (Khuzestani et al. 2017; Sulaymon et al. 2020) in the HYSPLIT model (online version available at <https://www.ready.noaa.gov/HYSPLIT.php>). The necessary meteorological data were obtained from the Global Data Assimilation System (GDAS) of the National Centers for Environmental Prediction (NCEP/NCAR), which offers better resolution due to the available meteorological series from 2007 to 2019. The trajectory calculation was performed considering three periods: before lockdown (BL), total lockdown (TL), and after lockdown (AL).

Statistical analyses

Statistical analyses were performed using the free open code R software (R Core Team 2019). We analyzed variables related to traffic (stratified by type of vehicle), meteorology, and pollutants per period (before lockdown (BL), partial lockdown (PL), total lockdown (TL), transition phase (TPh), and four economic recovery phases (Ph1, Ph2, Ph3, and Ph4)). Significant differences were tested using the nonparametric Kruskal-Wallis test (Conover 1999; Hollander et al. 2013).

Results and discussion

With the pandemic caused by COVID-19, the daily lives of individuals and all economic activities were affected at least mildly and, in some cases, drastically. The lockdown periods led to numerous changes, such as a reduction in or cessation of

commercial, industrial, and tourist activities, forcing a large portion of the population to stay at home. This situation led to a considerable reduction in the main sources of emission of atmospheric pollutants in cities.

Changes in concentrations of pollutants in PL, TL, TPh, Ph1, Ph2, Ph3, and Ph4 periods compared to BL period

The levels of the pollutants studied did not vary substantially in 2019 or the beginning of 2020 before the lockdown (BL) on February 16th, 2020. However, significant differences were found in the PL, TL, TPh, Ph1, Ph2, Ph3, and Ph4 periods for most of the pollutants studied (Fig. 2).

After the onset of the lockdown, significant reductions occurred in NO , NO_2 , NO_x , and CO in all periods. Considerable reductions in PM_{10} and $PM_{2.5}$ occurred only in the first four periods (PL, TL, TPh, and Ph1) (Fig. 3). However, the reduction in O_3 was non-significant in the PL period, followed by a slight increase in the TL, TPh, and Ph1 periods and a significant increase in the last three periods. Sulfur dioxide (SO_2) levels increased in all periods (Fig. 3).

The main anthropogenic sources of particulate matter are vehicular emissions, industrial activities, and the burning of wood, which are considered primary pollutants (US EPA 2016a). Although pyrolytic processes stemming from the vehicular fleet and industrial activities are the predominant sources of particulate matter in the atmosphere of the city of Fortaleza, the burning of wood and coal used as energy sources in commercial and industrial activities is also a source of these pollutants (Cavalcante et al. 2010; Cavalcante et al. 2016; Silva et al. 2016; Rocha et al. 2016). The lockdown periods led to a reduction in $PM_{2.5}$ and PM_{10} in the atmosphere of the city. In the PL, respective reductions of 50.5% and 34.3% in $PM_{2.5}$ and PM_{10} were found in comparison to the BL period. These reductions were respectively 46.4% and 34.9% in the TL period. Significant reductions were also found in the initial phases of economic recovery: 75.5% in $PM_{2.5}$ and 47.8% in PM_{10} in TPh and 68.6% and 33.6%, respectively, in Ph1. In the subsequent phases (Ph2, Ph3, and Ph4), drastic increases in $PM_{2.5}$ and PM_{10} levels were found in relation to the BL period, with a 72.1% increase in $PM_{2.5}$ in Ph4 (Fig. 7). Besides the imposed restrictions during the lockdown, the reduction in $PM_{2.5}$ levels may also be attributed to the simultaneous reduction in the concentration of precursors, such as volatile organic compounds (VOCs) and NO_x , which were significantly reduced in the period (US EPA 1996). Levels of particulate matter and nitrogen oxides underwent the most drastic reductions, as reported for the lockdown period in India (Sharma et al. 2020). The increase in $PM_{2.5}$ and PM_{10} levels found in the last two economic recovery phases (Ph3 and Ph4) is a consequence of the return

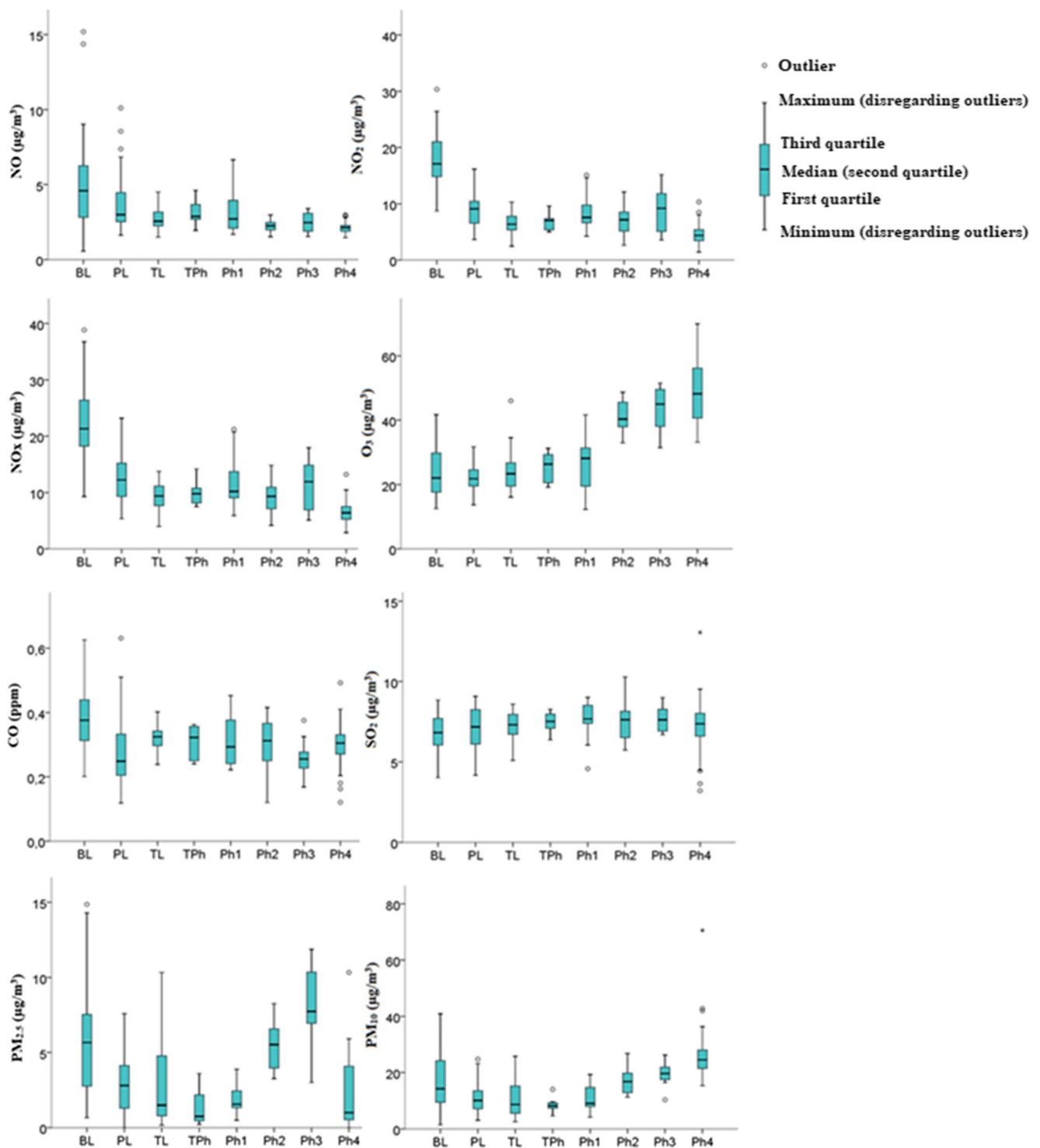


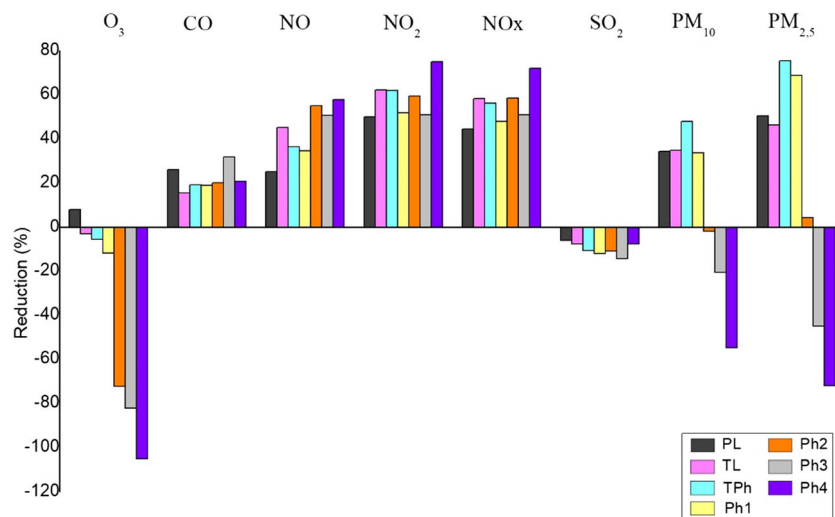
Fig. 2 Levels of pollutants analyzed

of activities in the city, such as the intensification of vehicular traffic.

Nitrogen monoxide (NO) and nitrogen dioxide (NO₂) are the most abundant nitrogen forms and are represented by NO_x (NO_x = NO + NO₂). Automobiles and other vehicular sources contribute about half of the NO_x emitted. Thus, NO_x gases are

linked to areas of high motor vehicle traffic, as these gases are generally produced from the reaction between nitrogen and oxygen during the combustion of fuels (Bootdee et al. 2012; US EPA 2020). NO₂ accounts for the largest fraction of NO_x in the air, whereas NO is predominant in emitting sources. NO₂ is formed mainly by the reaction between ozone (O₃)

Fig. 3 Pollutant levels in PL, TL, TPh, Ph1, Ph2, Ph3, and Ph4 periods compared to BL period



and NO, which is emitted by vehicles powered with fossil fuels (Carslaw and Beevers 2004; He et al. 2020).

As occurred with particulate matter, nitrogen oxides also diminished drastically in the two lockdown periods (Fig. 7), with reductions of 44.5% in NO_x, 25.1% in NO 25.1%, and 50.0% in NO₂ in the PL period compared to the BL period. These reductions were even greater in the TL period: 58.4%, 45.1%, and 62.2%, respectively. Significant reductions were also found in TPh and the subsequent economic recovery phases, especially Ph4, when these figures reached 71.2%, 57.8%, and 74.9% for NO_x, NO, and NO₂, respectively (Fig. 7).

The main sources of CO in the atmosphere are vehicles fueled by gasoline and diesel as well as other practices involving the burning of fossil fuels, such as industrial activities (US EPA 2016b). CO levels were also reduced in the lockdown periods and phases of moderate restrictions (TPh, Ph1, Ph2, Ph3, and Ph4), although to a lesser extent in comparison to NO_x. The concentration of CO was reduced by 26.1% in the PL period, 15.4% in the TL period, 19% in TPh, 18.9% in Ph1, 20.1% in Ph2, 31.9% in Ph3, and 20.6% in Ph4 (Fig. 7). The reduction was not progressive in the two lockdown periods and economic recovery phases, which may be explained by the fact that the drastic reduction in vehicular traffic in the city was not accompanied by a drastic reduction in industrial activities. In other cities submitted to lockdown periods, the reduction in CO levels was attributed exclusively to the reduction in vehicular traffic. In some cities, however, there was a combination of factors, such as the reduction in vehicular traffic, the cessation of industrial activities, seasonal changes, and a reduction in the use of heating systems due to the closing of workplaces in different sectors (Collivignarelli et al. 2020; Dantas et al. 2020; Kerimray et al. 2020; Mahato et al. 2020; Nakada and Urban 2020; Sharma et al. 2020; Tobias et al. 2020).

Concentrations of O₃ in the atmosphere did not follow the same pattern as that of the other pollutants studied during the lockdown periods. In the PL period, the concentration was reduced by only 8% compared to the BL period, whereas a 3.0% increase was found in the TL period, followed by a progressive and drastic increase in later phases: 5.6% in TPh, 11.8% in Ph1, 72.2% in Ph2, 82.3% in Ph3, and 105.3% in Ph4 (Fig. 7). The increase in O₃ levels in the TL period must be due to the greater restriction in this period compared to the PL period, as observed in many cities submitted to lockdowns (Collivignarelli et al. 2020; Kerimray et al. 2020; Mahato et al. 2020; Nakada and Urban 2020; Sharma et al. 2020; Tobias et al. 2020).

O₃ is produced photochemically in the troposphere as a result of a complex set of reactions that involve NO_x and VOCs (Finlayson-Pitts and Pitts 2000). There are several possibilities for O₃ to undergo an increase rather than a reduction. Most studies report that a reduction in NO levels in the atmosphere during lockdown periods led to the accumulation of O₃ in the atmosphere due to the absence of its main eliminator (i.e., NO + O₃ = NO₂ + O₂) (Peralta et al. 2019; Sharma et al. 2020). According to Dantas et al. (2020), NO_x-focused strategies to reduce O₃ in VOC-limited areas should be evaluated carefully due to the increase in biogenic emissions of isoprene and VOCs. Moreover, photochemical activity and temperature are the main factors in the production of O₃ in urban areas (Peralta et al. 2019).

The Brazilian fleet of diesel vehicles uses 20% biodiesel, which is a known emitter of aldehydes and VOCs into the atmosphere of cities (Rodrigues et al. 2012). During the lockdown periods in the city of Fortaleza, the fleet of light vehicles was considerably diminished. In contrast, the fleet of diesel vehicles (i.e., cargo vehicles and public transportation) increased drastically, especially during the stricter TL period (Fig. 5). Another possible explanation for the increase in O₃

is the higher incidence of sunlight during the lockdown periods (Kerimray et al. 2020).

The main sources of SO₂ in the atmosphere are the combustion of fossil fuels by vehicles and power plants as well as other industrial activities, such as mining (US EPA, 2019). SO₂ levels increased by 6.1% in the PL period compared to the BL period, and this increase was even higher in the TL period (7.6%). In the following phases, when activities gradually returned, more significant increases were found: 10.6% in TPh, 12% in Ph1, 11% in Ph2, 14.3% in Ph3, and 7.6% in Ph4 (Fig. 7). An increase rather than reduction in SO₂ levels was also found in other cities submitted to lockdowns. Kerimray et al. (2020) considered the 7% increase in SO₂ levels to be statistically non-significant, and most studies report that emissions from vehicular traffic did not affect these levels, since the burning of coal continued in many industries that did not cease their activities (Kerimray et al. 2020; Sharma et al. 2020).

Traffic data

Vehicular traffic in urban areas is responsible for a large part of the pollutants in the atmosphere (WHO; MS). The vehicular fleet has a high average age and state of depreciation, which leads to an increase in air pollution. The National Public Transport Association (ANTP) has developed the Information System on Urban Mobility (SIMOB). This system includes data on scrapping rates for the vehicular fleet, which is an important variable to consider when analyzing vehicle depreciation. According to data from the National Department of Motor Vehicles (DENATRAN), the size of the fleet in Fortaleza indicates that the city has a high motorization rate (Table 2). However, one should bear in mind that not all licensed vehicles in the city circulate in Fortaleza; many circulate in other municipalities. Moreover, the data include vehicles that may no longer be in circulation. However, these data have value and enable comparisons to other locations.

Data from DENATRAN highlight the significant participation of motorcycles in the composition of the fleet (28.6%) of Fortaleza. The city has a high motorization index (42.4 vehicles for every 100 inhabitants). Other municipalities of

the metropolitan region together have a rate of 14.9 vehicles/100 inhabitants, with a high contribution of motorcycles to this rate (8.4 cars/100 inhabitants and 6.6 motorcycles/100 inhabitants). Furthermore, the DENATRAN historical series shows that the total fleet registered in the city of Fortaleza grew by 195% in the period from 2001 to 2019, whereas the motorcycle fleet increased by 512% in the same period.

Considering all modes of transport, five million trips per day are estimated for the city of Fortaleza. The main reasons for which are getting to and from work and school. Most trips involve motor vehicles, and the destination of many is the center of the city and surrounding areas. According to Sousa et al. (2019), trips in the city of Fortaleza are predominantly performed by public transportation, with emphasis on trips for work purposes among the low-income portion of the population and trips to schools.

The traffic data was gathered by two electronic devices (RS Control model) controlled by the Municipal Traffic Agency (AMC)—one in each direction around the air quality monitoring station. This equipment consists of a fixed speed control radar and traffic volume counter using images with precision greater than 95% for the recording of speed and 90% for the traffic count. The traffic volume data was aggregated every 15 min according to vehicle type in the period from February 1st to November 30th, 2020. The data were divided into blocks based on the decrees established by the state government: before lockdown (BL) from February 1st to March 16th; partial lockdown (PL) from March 17th to May 7th; total lockdown (TL) from May 8th to 31st; transition phase (TPh) June 1st to 7th, and subsequent economic recovery phases—phase 1 (Ph1) from June 8th to 21st, phase 2 (Ph2) from June 22nd to July 5th, phase 3 (Ph3) from July 6th to 19th, and phase 4 (Ph4) from July 20th to November 30th. The effect of social distancing measures on vehicular traffic is illustrated in Figure 4.

A gradual decrease in traffic volume occurred after the BL, followed by a gradual increase beginning with the TPh. Moreover, the volume of vehicular traffic was more concentrated on working days (Monday to Friday), with a reduction on the weekends (Saturday and Sunday), as shown by the horizontal lines, which represent the median of the sample, and the x cross, which represents the mean. The upper limits indicate the maximum value in the sample and varied with the periods of restrictions and return to economic activities. It is noteworthy that a nearly total return to social and economic activities occurred since the TPh, but with limitations on the gathering of crowds. The relative change in vehicular traffic in the period of interest is shown in Figure 5.

Figure 5 shows maximum traffic reduction between the TL and PL periods, followed by growth beginning in the transition period, in which circulation and the operation of most commercial establishments were allowed, but with a need for the sanitation of spaces and restrictions regarding the

Table 2 Fleet of vehicles in Fortaleza and metropolitan region

Vehicle type	Fortaleza	Metropolitan region
Cars	743,777	928,727
Motorcycle	323,236	469,175
Trucks	26,735	39,731
Buses	10,397	14,225
Others	27,416	35,677
Total	1,131,361	1,487,535

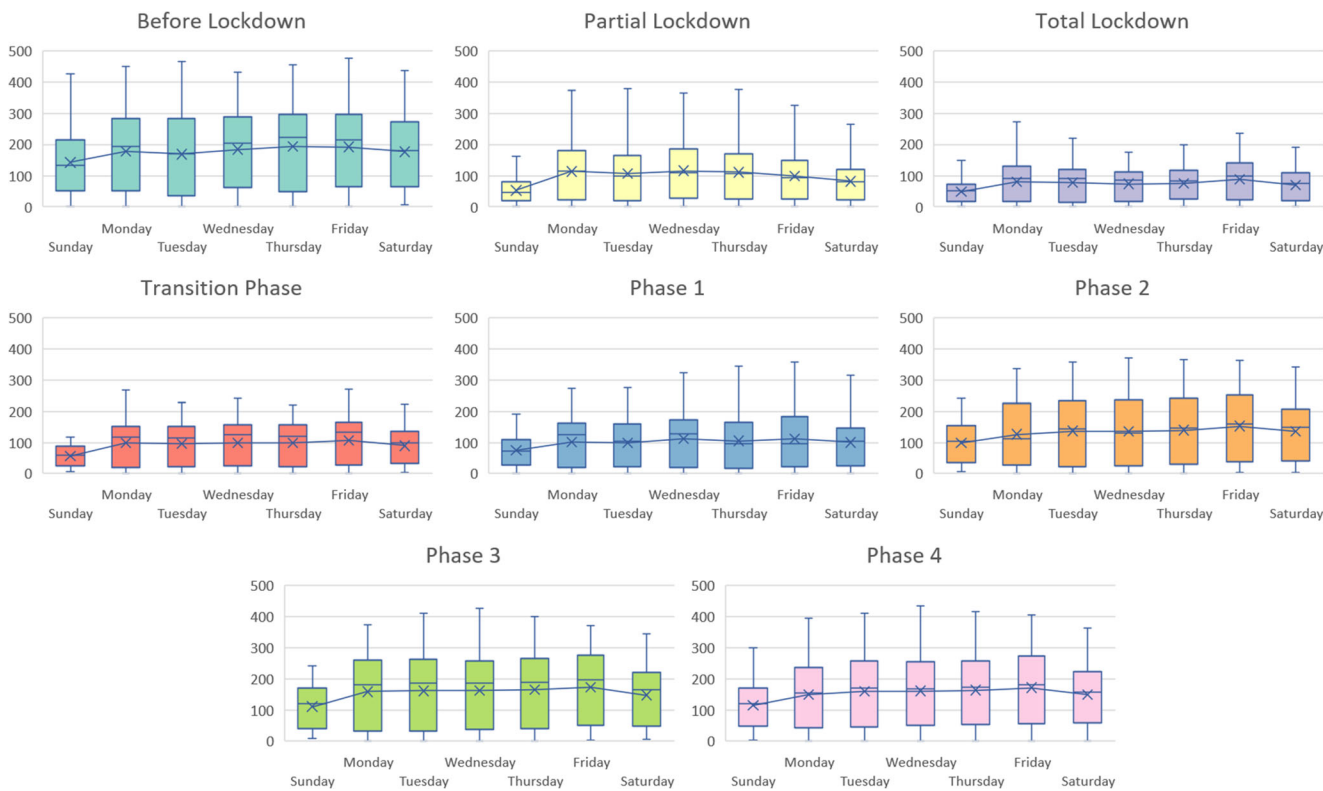


Fig. 4 Effect of social distancing measures on vehicular traffic

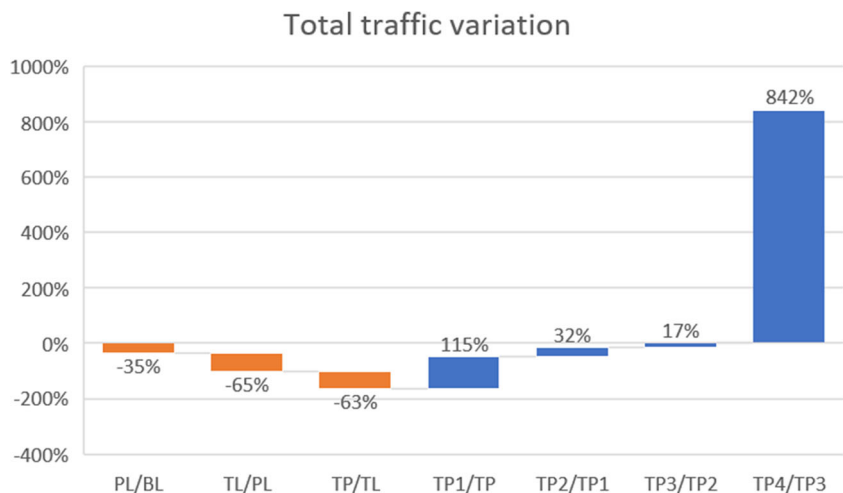
gathering of people. Figure 6 displays the results of the analysis according to vehicle type.

Figure 6 shows a pattern of gradual reduction in vehicular circulation, followed by an increase starting in the TPh, with the exception of buses. This reveals a complicated problem, as the part of the population that provides essential services uses buses as the major mode of transportation. The upper limits in Ph2 and Ph4 differ from that of the BL period, revealing that the return of public transportation was insufficient and exerted a negative impact on habitual users of the public system. Thus, a portion of the population has been subjected to a poor public

transportation performance as well as problems with vehicle sanitization. The other vehicles had very similar circulation. Motorcycles were widely used for delivery services, and heavy vehicles were used for transporting goods. Passenger cars were widely used for individual transport, as this was a way to reduce exposure to the coronavirus. Figure 7 shows the relative changes between the periods analyzed for each vehicle type.

The pattern of variation in vehicular circulation was similar, except for motorcycles and buses. An increase in motorcycle circulation was found in the PL and BL periods, and a

Fig. 5 Variation in vehicular traffic during period analyzed



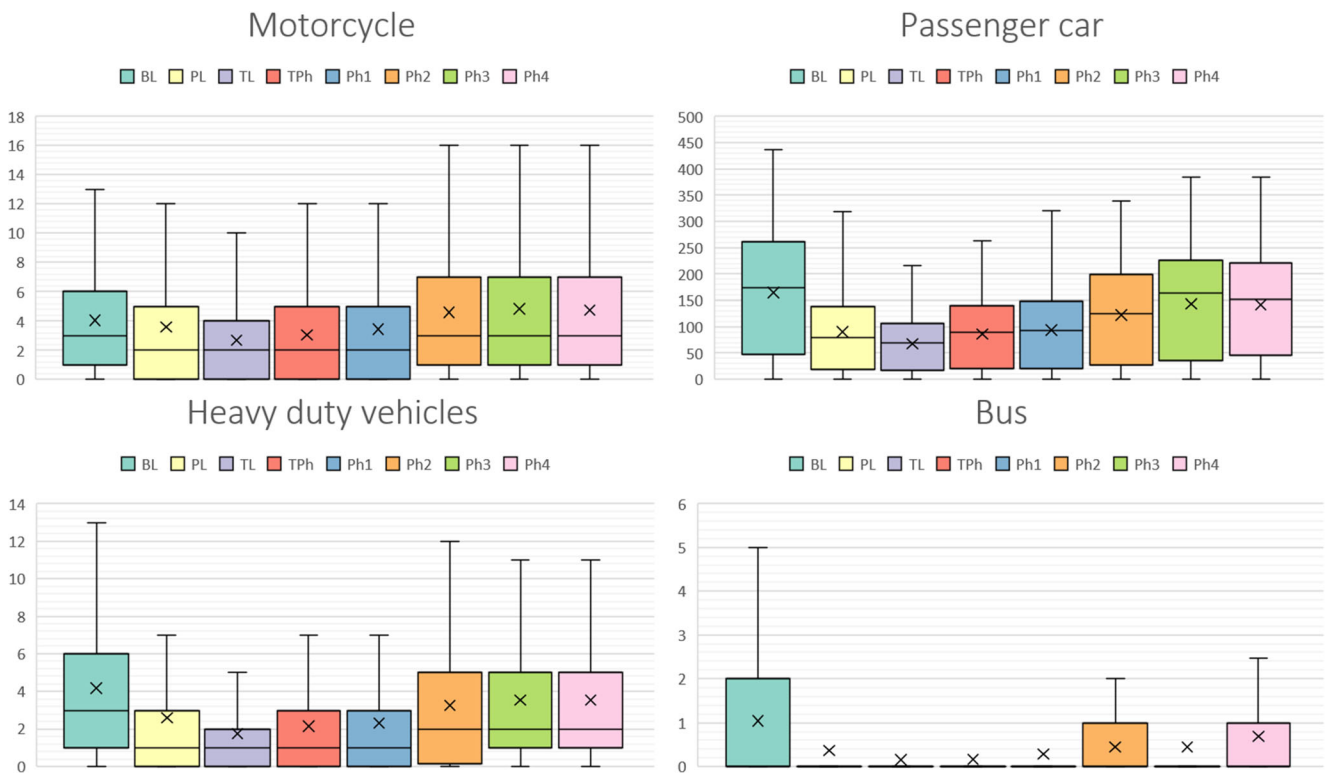


Fig. 6 Traffic by vehicle type during periods analyzed

reduction in bus circulation was found in the Ph2 and Ph3 periods. Motorcycles were and continue to be widely used

for deliveries, and the bus fleet has had a low operational performance since the beginning of the restrictive measures.

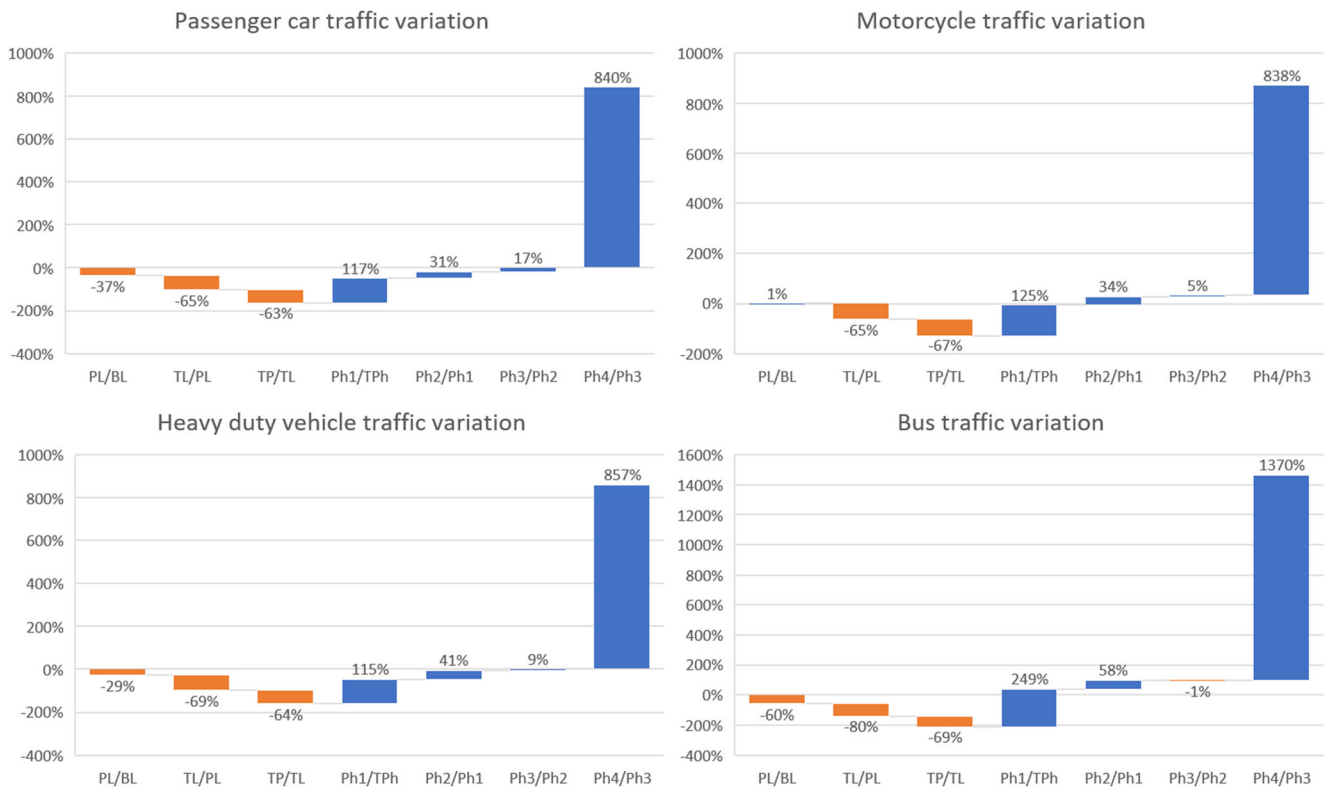


Fig. 7 Relative variation in periods analyzed by vehicle type

Variations in meteorological data

Higher temperatures and solar radiation as well as lower precipitation and relative humidity were found in the period studied (Fig. 8). Days of rainfall occurred between February and June, but the greatest concentration occurred in the week from June 1st to 16th (TPh and Ph1 periods in the city of Fortaleza). The other months had lower rainfall and relative humidity, with isolated days of rain.

Figure 8 shows that the second half of the year had higher wind speeds, less precipitation, and a higher incidence of sunlight compared to the first half of the year.

The diurnal cycle of planetary boundary layer height (PBL_{height}) determined from the ERA-5 dataset for the study period, which is characterized by variation between daytime and nighttime vertical profiles, is illustrated in Figure 9. Maximum PBL_{height} (see color bar in Figure 9) over the city of Fortaleza was lower in the rainy season than the dry season. PBL_{height} ranged from 1062 to 1149 m in the rainy season and 1230 to 1712 m in the dry season. The maximum PBL_{height} for each study period is provided in Table 3.

PBL_{height} reached its maximum value at 12:00 h (local time) in the rainy season and between 13:00 h and 15:00 h (local time) in the dry season, except for the day September 1st, 2020 (11:00 h—local time). Maximum PBL_{height} at these times was due to large sensible heat flux values.

The influence of meteorological variables and traffic during the periods studied was evaluated using the nonparametric Kruskal-Wallis test to determine the occurrence of significant differences between groups (Hollander et al. 2013). A considerable correlation was found among the pollutants NO_x, NO, NO₂, and O₃. PM_{2.5} and PM₁₀ were positively correlated with each other, and PM₁₀ was correlated with O₃, probably due to the influence of the predominant sources in the region, such as the vehicular fleet (Fig. 10a). In contrast, CO and SO₂ were not correlated with any of the pollutants or with each other, demonstrating that these compounds do not originate from the vehicular fleet or the activities that were ceased/reduced (Fig. 10a,b).

Strong correlations were found between most pollutants and meteorological variables. Relative humidity, wind speed and direction, precipitation, and PBL height had the strongest highest correlations with PM₁₀, NO_x, NO₂, NO, and O₃, showing direct influences on the concentrations of these pollutants in the air, as solar radiation is one of the variables involved in the formation of ozone in the atmosphere (Peralta et al. 2019). Moreover, the PBL was strongly influenced by wind speed and solar radiation, as demonstrated by the correlations shown in Figure 10a.

The lockdown period exerted an influence on all variables related to traffic, independently of the type of vehicle. A reduction in traffic volume was found in comparison to the BL period. SO₂ had negative correlations with other variables and

was therefore not influenced by the lockdown periods, whereas the other pollutants were influenced by the lockdown to different degrees, demonstrating that vehicular emissions are one of the predominant sources in the region (Fig. 10a,b). This is explained by the fact that the lockdown periods may not have been effective, as commercial and industrial activities continued operating and public transportation was also needed.

Significant negative correlations were found between the diurnal cycle of PBL_{height} and NO_x (−0.73), NO₂ (−0.73), and NO (−0.64). Moreover, significant positive correlations were found with O₃ (0.81) and PM₁₀ (0.6), indicating that the diurnal variation in PBL_{height} plays an important role in the concentration of ground-level pollutants.

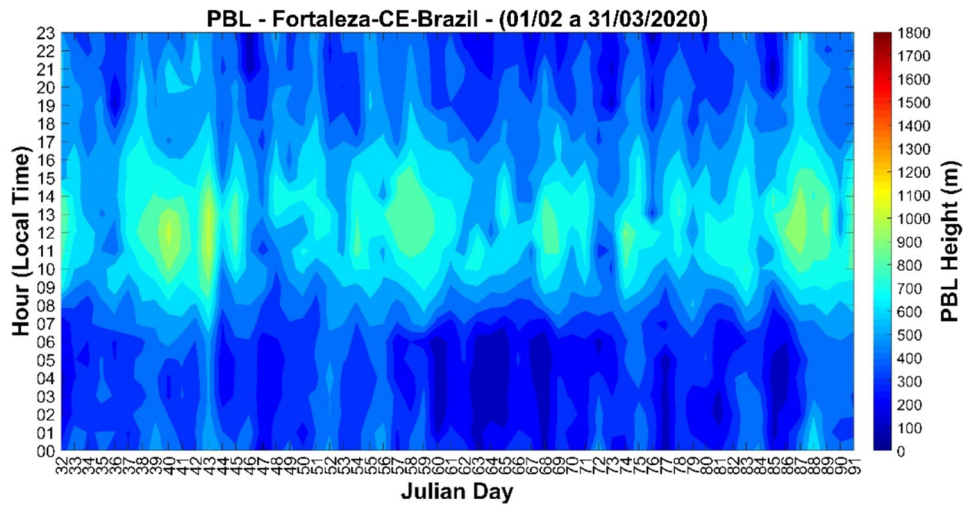
Cancer risk

Figure 11 shows cancer risk related to PM_{2.5} in the BL, PL, TL, TPh, Ph1, Ph2, Ph3, and Ph4 periods for people in general, those never smoked (non-smokers), and ex-smokers. The graph also shows the risk of cancer classified using the PM_{2.5} concentration criteria (maximum permitted value of PM_{2.5} in 24 h) recommended by the WHO and adopted by CONAMA Resolution 491/2018 (National Environment Council, BRASIL 2018).

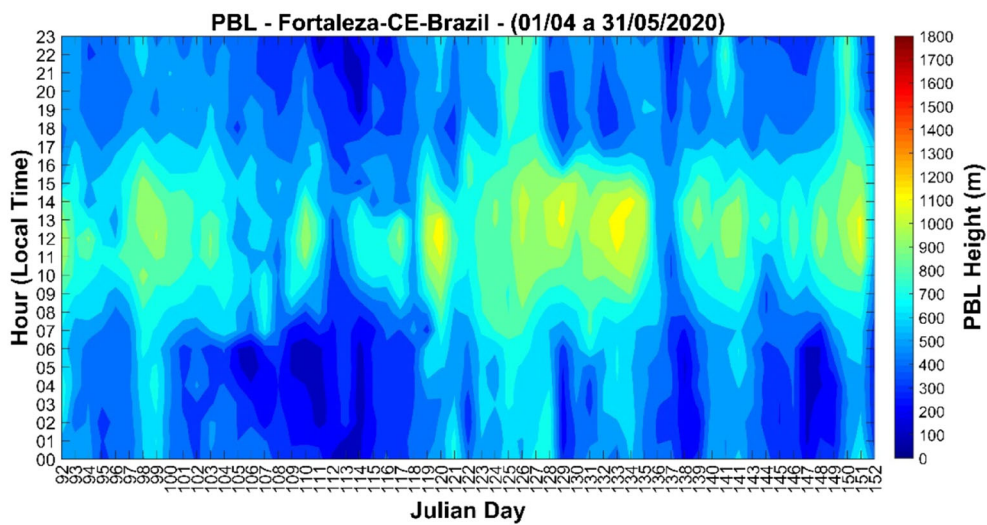
The risk of cancer associated with PM_{2.5} decreased in the two lockdown periods (PL and TL) compared to the previous period (BL) for the three classes analyzed. The lowest risks were observed in the two periods after the lockdown (TPh and Ph1), followed by a drastic increase in the last three economic recovery periods (Ph2, Ph3, and Ph4). The results showed that the risk was always greater among ex-smokers than non-smokers (Fig. 11).

Cancer risk due to PM_{2.5} was estimated considering the recommended exposure limits proposed by the World Health Organization and US EPA. Studies conducted in more than 30 countries have recently revealed that each 10 μg m^{−3} increase in PM_{2.5} levels in the air has corresponded to a 9 to 36% increase in lung cancer rates in recent years (Raaschou-Nielsen et al. 2013; Hamra et al. 2014). The International Agency for Research on Cancer (IARC) recently classified external atmospheric particles (particles suspended in the air in outdoor/open environments) as Group 1 carcinogens (causing cancer to humans) because these particles cause permanent mutagenesis, heart attacks, diseases related to changes in blood pressure, and premature death (Hamra et al. 2014). Unfortunately, studies on cancer risk are scarce, and we therefore compared our data to the few cancer risk studies conducted in outdoor environments.

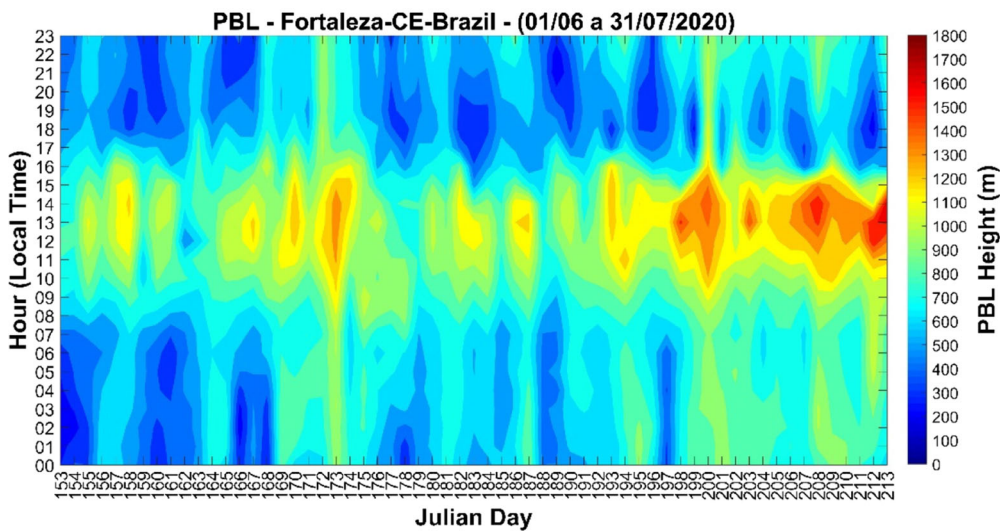
The risk of cancer was calculated only for men, as the risk of cancer for women is about 6% higher than that for men. According to Cavalcante et al. (2005, 2006) and Sousa et al.



(a)



(b)



(c)

◀ **Fig. 9** ERA-5 data of planetary boundary layer (PBL) height for a February to March 2020, b April to May 2020, c June to July 2020, d August to September 2020, e October to November 2020. ERA time was converted from UTC to local time

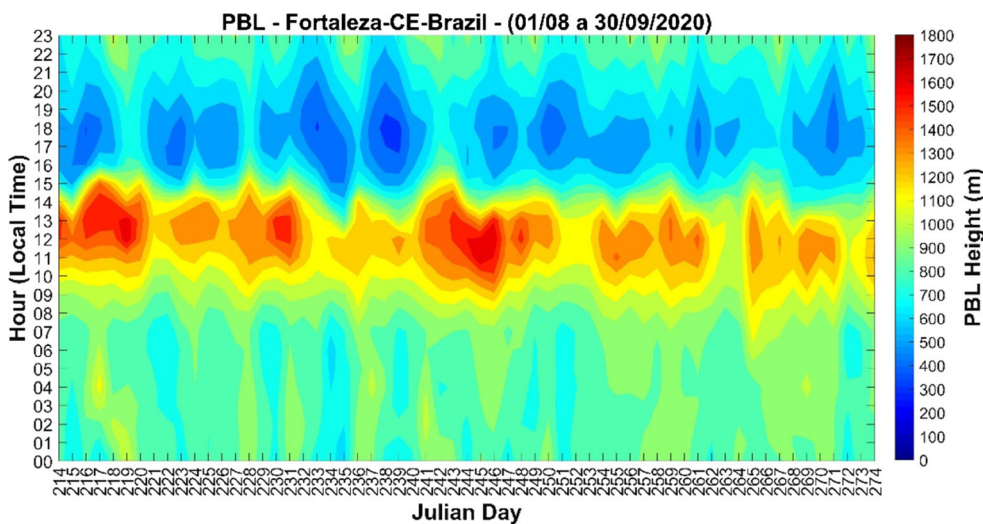
(2011), this occurs when using a linear cancer risk assessment model.

During the period before social distancing (BL), concentrations of respirable particulate matter were higher due to the greater movement of vehicles in the city of Fortaleza, with a consequent increase in the concentration of $PM_{2.5}$. Thus, the risk of cancer was also higher in this period. With the reduction in vehicular traffic during periods of social distancing (PL and TL), the concentrations of this air pollutant decreased and

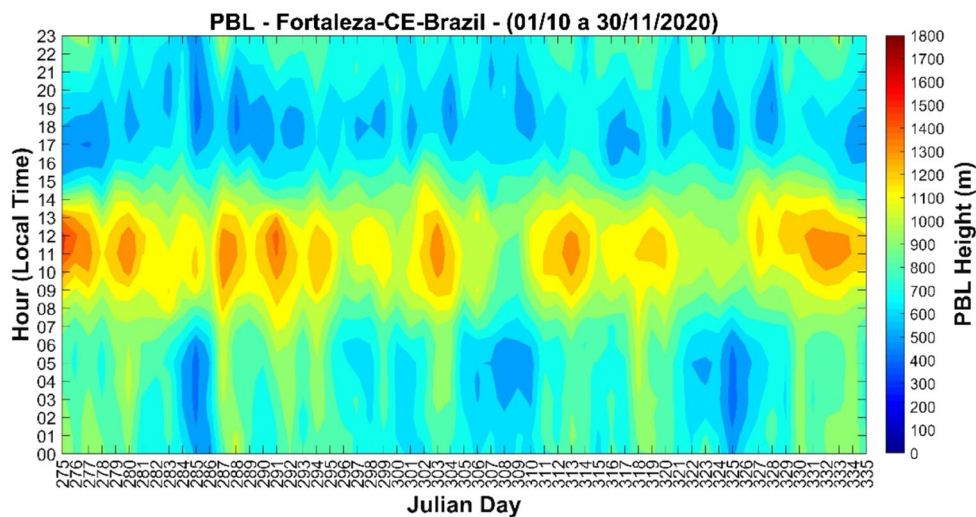
were accompanied by a nearly 50% reduction in the risk of cancer associated with exposure to $PM_{2.5}$ compared to the BL period.

The risk of cancer was reduced by half during the lockdown periods compared to the BL period. However, the reduction in cancer risk was lower in the PL compared to the TL, which may be due to the slight increase in the vehicular fleet and the number of days with rainfall in the last week of the TL. According to Rocha et al. (2016), $PM_{2.5}$ is inversely correlated with precipitation because rain serves as a cleaner of the atmosphere.

A gradual return to economic activities occurred in June 2020, with security measures maintained and limitations imposed on the gathering of people. In this return period,



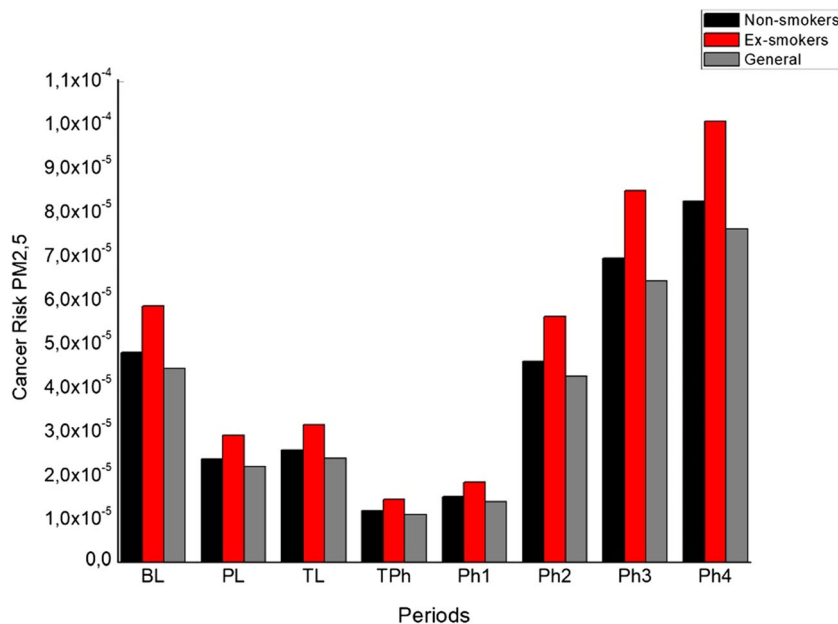
(d)



(e)

Fig. 9 (continued)

Fig. 11 Estimate of cancer risk due to PM2.5



particulate matter in the environment is accompanied by a 22% increase in the risk of dying from any type of cancer, a 42% higher risk of death by cancer in the digestive tract, and a 35% increase in the occurrence of tumors in the liver, biliary tract, and pancreas. Moreover, an increase of 10 $\mu\text{g m}^{-3}$ in exposure to particulate matter is accompanied by an 80% increase in the risk of death from breast cancer among women and a 36% increase in the risk of death due to lung cancer among men.

A study by Ribeiro et al. (2019) conducted in the city of São Paulo estimated a relative risk of 1.09 (95% CI: 1.02–1.15) and 1.19 (95% CI: 1.10–1.29) of hospital admission due to cancer of the respiratory system with every standard deviation increase in traffic density and the municipal human development index, respectively. There was also a clear exposure-response gradient regarding hospitalization for respiratory cancer in relation to the increase in vehicular traffic (IRR = 1.11; 95% CI: 1.07–1.15, for every ten units of increased traffic density).

One should bear in mind that the calculation of cancer risk considers long-term exposure (35 years) and predicts a scenario in which the PM concentration remains for a long period. Thus, if the lockdown or reduced urban activities were maintained in the long term, the health risk would be much lower compared to periods in which all or most urban activities function normally.

Pollutant trajectory

From the HYSPLIT modeling, dispersion trajectories of the pollutants were obtained from the collection point, and the behavior in the vertical atmospheric profile observing the

height pollutants can reach during the trajectory, as shown in Figure 12.

In the BL period (Fig. 12a), the direction of the pollutant dispersion trajectory was predominantly southwesterly (SW), as the prevailing meteorological condition was winds from the northeast (NE). The vertical atmospheric profile revealed altitudes of up to 500 m throughout nearly the entire trajectory, with higher elevation of the pollutant dispersion plume at the end of the trajectory, which may have reached altitudes above 2500 m. In the TL period (Fig. 12b), a change in the winds occurred in the region, with the pollutant dispersion trajectory predominantly westerly (W), influenced by winds from the east (E). Winds in the east quadrant are very characteristic of the state of Ceará and governed the dispersion of pollutants to the west in this period. In the vertical atmospheric profile, altitude during the TL was generally low to 500 m, reaching up to 1250 m at some points of the trajectory, revealing lower altitudes compared to the BL period. This behavior may be associated with the lower wind speed in the TL. In the AL period (Fig. 12c), the influence of winds from the southeast (SE), which direct the dispersion of the pollutants to the northwest (NW), was clearly noticeable. SE winds are also quite characteristic of Ceará and were the main drivers of the dispersion of pollutants in this period. During the AL, higher altitudes of the pollutant dispersion plume were reached, with a predominance of between 1000 and 2000 m in height observed in this trajectory and some points even exceeding 4000 m. The greater dispersion in the vertical atmospheric profile in comparison to the other periods may have occurred due to the influence of the higher wind speed, which enables the expansion of the pollutant plume in the atmosphere.

Despite the wind being the governing factor in the dispersion of PM and the determination of its trajectory, the

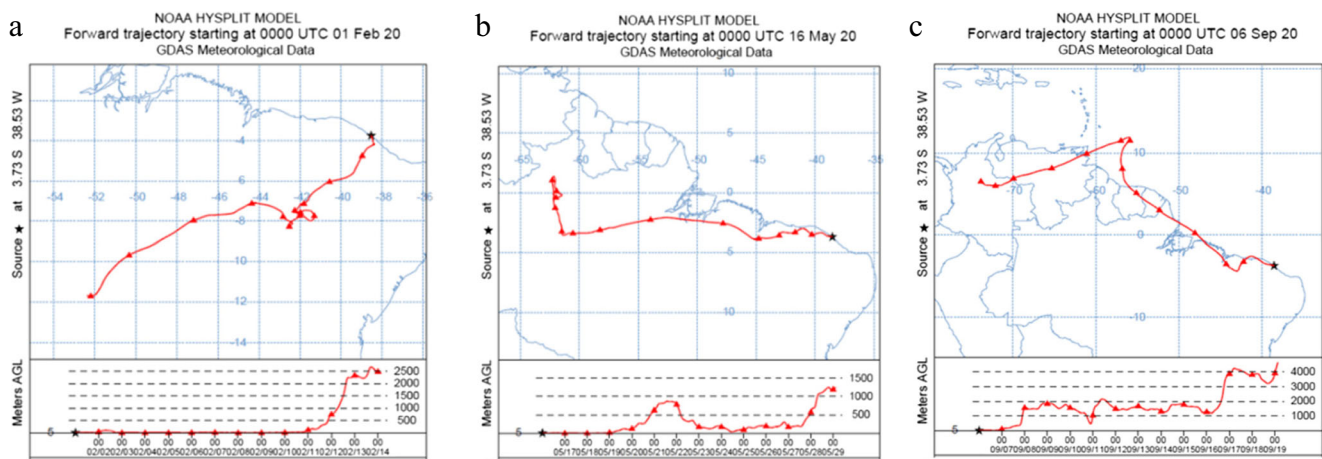


Fig. 12 Backward trajectory of pollutants. a Before lockdown (BL). b Total lockdown (TL). c After lockdown (AL)

concentration of pollutants is also fundamental to the analysis. Thus, if the sources of pollution decrease, as occurs in lockdown periods, the region receiving the dispersed pollutants will be less affected due to the lower concentrations.

Conclusion

The lockdown periods caused by the pandemic in 2020 led to many changes in the life of the population and air quality in the city of Fortaleza. With the reduction in commercial, industrial, and other urban activities, such as vehicular movement, a drastic reduction occurred in the concentration of the atmospheric pollutants CO, NO, NO₂, and NO_x in all lockdown periods analyzed. Levels of PM_{2.5} and PM₁₀ were reduced in the four first phases (partial lockdown, total lockdown, transition phase, and economic recovery phase 1), followed by increases in the concentrations of these pollutants in the subsequent two phases. O₃ and SO₂ behaved inversely to other pollutants, with an increase in concentrations during the lockdown periods.

Local meteorology strongly influences the behavior of atmospheric pollutants. Relative humidity, wind speed and direction, precipitation, and PBL height had the strongest correlations with PM₁₀, NO_x, NO₂, NO, and O₃, revealing that these variables are important to maintaining the air quality of the city.

The total or partial lockdown of urban activities during the period studied was also effective at reducing health risks related to air pollution (PM_{2.5}) in the long term. In the partial lockdown, total lockdown, transition phase, and economic recovery phase 1, the risk of cancer was significantly reduced compared to the period prior to lockdown and other phases of economic recovery (Ph2 and Ph3), revealing that if the PM_{2.5} concentrations were kept low

for the long term, the risk to the health of the population would also reduce considerably.

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Declarations

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Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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