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Short-Term Associations between Morbidity and Air Pollution in Metropolitan Area of Monterrey, Mexico

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Abstract: Short-term effects of air pollution on the number of hospital admissions in eight municipalities of the Metropolitan Area of Monterrey, Mexico, were assessed from 2016 to 2019 using a time-series approach. Air quality data were obtained from the Atmospheric Monitoring System of Nuevo Leon State (SIMA) which belongs to SINAICA (National System of Air Quality Information), providing validated data for this study. Epidemiological data were provided by SINAIS (National System of Health Information), considering admission by all causes and specific causes, gender and different age groups. Guadalupe had the highest mean concentrations for SO_2, CO and O_3; whereas Santa Catarina showed the highest NO_2 concentrations. Escobedo and Garcia registered the highest levels for PM_{10}. Only PM_{10} and O_3 exceeded the permissible maximum values established in Mexican official standards. A basal Poisson model was constructed to assess the association between daily morbidity and air pollutants, from this, a second scenario in which daily mean concentrations of air pollutant criteria increase by 10% was considered. Most of pollutants and municipalities studied showed a great number of associations between an increase of 10% in their current concentrations and morbidity, especially for the age group between 5 and 59 years during cold months, excepting ozone which showed a strongest correlation during summer. Results were comparable to those reported by other authors around the world, however, in spite of relative risk index (RRI) values being low, they are of public concern. This study demonstrated that considering the nature of their activities, economically active population and students, they could be more vulnerable to air pollution effects. Results found in this study can be used by decision makers to develop public policies focused on protecting this specific group of the population in metropolitan areas in Mexico.

Keywords: morbidity; air pollution; health; Monterrey; Mexico

1. Introduction

Health effects of human exposure to air pollution can be either long or short-term, and different pollutants may have significantly different exposure-response characteristics [1,2]. Although individual atmospheric pollutants have their own specific toxic effects on human health, O_3, NO_2, PM_{10} and $PM_{2.5}$ share the common property of being potential oxidants. Particulate matter penetrates into the airways causing harmful impacts to human health, and SO_2 is a toxic gas which is related to respiratory and pulmonary diseases [3]. Therefore, air pollution can increase hospital admissions due to respiratory and cardiovascular diseases as asthma attacks, acute bronchitis and lung function decline [4].

Reviews on associations between air pollution and epidemiology report incidence or prevalence of a specific health effect with air pollutants as criteria [5,6], and most evidence on effects of air pollution on morbidity and mortality has been based on results from time-series analysis. However, in spite of such associations often being weak (less than 1.3), some differences have been reported due to potential confounding pollutants, collinearity and differences in the studied population. Lipfert [5] identified 417 long-term studies of air quality and health, and found that 54% of them reported a significant association with at least one pollutant, cardiovascular and respiratory causes being the most important. Lipfert [5] also reported that by pollutant, the highest ratios are often found for TSP, O_3 and NO_2 in the case of respiratory effects. PM_{10} leads to cardiovascular diseases such as myocardial infarction, stroke, heart failure and venous thromboembolism.

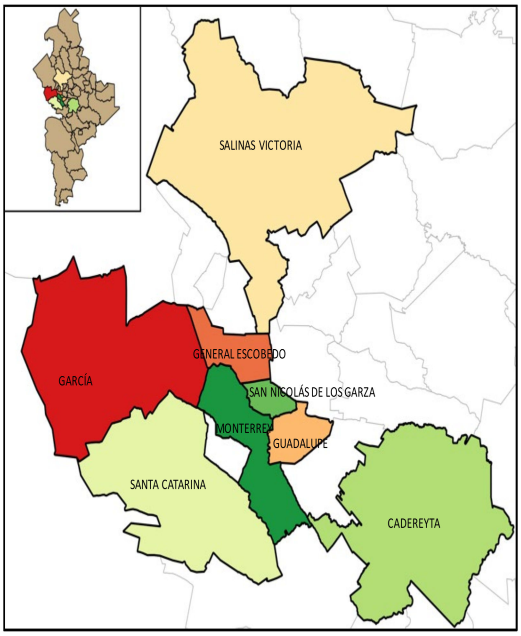
In recent years, episodes of high concentrations of atmospheric pollutants have led to an increase in the number of hospital admissions, mainly of cardiovascular and respiratory origin. It has been observed that the incidence is higher in people who have previously suffered from cardiorespiratory diseases [7]. Epidemiological studies have shown that the exposure to atmospheric pollutants also has an effect on the circulatory system. De Pablo et al. [8] found positive and statistically significant associations between variations in concentration levels of SO_2, O_3 and NO_2 with morbidity, mainly for people older than 69 years. This association was greater for cardiovascular type diseases than for respiratory. Khaniabadi et al. [3] found that an increase of 10 μg m^{-3} in SO_2 levels increased the morbidity by 2.7%. About 3.9% for cardiovascular mortality, 3.9% for respiratory diseases and 4.4% for cardiovascular disease for ambient PM_{10}; and about 7.3% for total mortality, 12.1% for cardiovascular mortality and 3% for respiratory mortality for $PM_{2.5}$, respectively, are attributed to concentration increases of 10 μg m^{-3} in Iran. Furthermore, 3.2% of cardiovascular disease and chronic obstructive pulmonary disease and 4.2% of acute myocardial infarction can be attributed to SO_2 concentration increases of 10 μg m^{-3} [3].

In addition, Romieu [9] observed significant associations between ozone ambient levels and emergency visits related to respiratory problems in children. Ozone exposure was also related to lower respiratory infections with a 4-day lag in children aged five years or less. An increase of 20 ppb in the maximum 8-h moving average of ozone was related to a 12.7% increased risk. Cerón et al. [10] studied the short-term effects of air pollution on health in the Metropolitan Area of Guadalajara, considering daily mortality by all causes, by specific cause (circulatory and respiratory) and different age groups, finding that the most vulnerable sector of the population corresponded to adults over 60 years of age. Cerón et al. [11] studied the correlation between daily mortality and air pollution in the Metropolitan Area of Monterrey, considering all causes, by specific cause (circulatory and respiratory), different age groups and episodes of extreme temperatures resulting from climatic change, assessing its effect on relative risk indexes. Their results showed that people >60 years old was more vulnerable not only to air pollution, but also high temperatures in semiarid places, such as Monterrey, as a result of climatic change. The above-mentioned studies did not evaluate the relationship between morbidity (hospital admissions) and levels of atmospheric contamination.

Studies conducted in Latin America provide enough evidence of the adverse effects of air pollutant criteria on human health, mainly on vulnerable and susceptible population groups [9]. On the other hand, published studies have shown that reduced concentrations of O_3, PM_{10} and $PM_{2.5}$ in the United States have resulted in the prevention of associated morbidities as well as significant improvements in life expectancy [1,12,13]. Air quality can be improved by establishing federal standards in response to evidence derived from these types of studies, indicating levels at which adverse health effects have been observed. In this way, federal standards can be adjusted to protect public health, especially vulnerable people. Another purpose is to provide information that can be useful to make air quality management decisions at local and regional scale. Therefore, in this study, we aimed to describe hospital admissions and meteorological and pollutant variables, to construct a basal Poisson model in order to assess the association between daily morbidity and air pollutants, and to determine which atmospheric variables or pollutants show the strongest short-term relationship with daily morbidity in eight municipalities of the Metropolitan Area of Monterrey (MAM) during 2016–2019, considering all age groups, all causes and causes of specific diseases (respiratory and circulatory).

2. Study Area

The Metropolitan Area of Monterrey (MAM) is constituted of Monterrey City and twelve more municipalities in the state of Nuevo Leon. According to INEGI [14], is the second greatest metropolitan area in Mexico with 5,341,171 inhabitants, and has the second greatest territorial extension. In this study, only eight municipalities (including Monterrey) were considered, since SIMA only has atmospheric monitoring stations in these municipalities. García, Cadereyta and Salinas Victoria are the municipalities with the greatest territorial extension, whereas Monterrey, Guadalupe and General Escobedo are the more populated municipalities; Salinas Victoria and Cadereyta being the less populated municipalities. Climate in MAM is calid semiarid (Bsh) with the influence of a subtropical climate (Cwa). The annual mean precipitation is 600 mm, occurring during the summer months, September being the rainiest month of the year. The study area is constituted of eight municipalities in Nuevo Leon state, including Monterrey City, in which SIMA has monitoring stations integrated into SINAICA; their locations are shown in Figure 1.



Municipality	Geographical Location (SIMA station)
Monterrey	25.68 °N 100.34°W (Center)
San Nicolás de los Garza	25.75°N 100.26°W (Northeast)
General Escobedo	25.76°N 100.37°W (Northwest)
García	25.78°N 100.59°W (Northwest)
Salinas Victoria	25.8°N 100.34°W (North)
Guadalupe	25.67°N 100.25°W (Southeast)
Cadereyta	25.65°N 100.1°W (Southeast)
Santa Catarina	25.68°N 100-46°W (Southwest)

Figure 1. Location of municipalities of the study area in Monterrey, Nuevo Leon, Mexico.

3. Materials and Methods

3.1. Air Quality Data

The Federal Government of Mexico is responsible for establishing air quality standards to protect public health and monitoring compliance. These standards are published in the Mexican Official Regulations (NOM) and are applicable at national scale. There are two kinds of NOMs, environmental health NOMs which establish the maximum permissible limits for criteria pollutants, and technical NOMs which define the measurement standardized methods. Monitoring stations from SIMA consider both kinds of NOMs, and their performance is evaluated by SINAICA on a national scale. Tables 1 and 2 describe reference values of air quality standards and reference methods for the measurement of air pollutants, respectively.

Table 1. Mexican air quality standards and their maximum permissible limits for each pollutant criteria.

Air Pollutant Criteria	NOM	Publication Date	Description
SO_2	NOM-022-SSA1-2010 [15]	08/09/2010	0.110 ppm, maximum 24-h mean 0.200 ppm second annual maximum 8 h moving average 0.025 ppm, annual mean
CO	NOM-021-SSA1-1993 [16]	23/12/1994	11.0 ppm annual maximum 8 h moving average
NO_2	NOM-023-SSA1-1993 [17]	23/12/1994	0.210 ppm, hourly mean
O_3	NOM-020-SSA1-2014 [18]	19/08/2014	0.095 ppm, hourly mean 0.070 ppm, annual maximum 8 h moving average
PM_{10}	NOM-025-SSA1-2014 [19]	20/08/2014	75 μg m^{-3}, 24-h mean 40 μg m^{-3}, annual mean
$PM_{2.5}$	NOM-025-SSA1-2014 [19]	20/08/2014	45 μg m^{-3}, 24-h mean 12 μg m^{-3}, annual mean

Table 2. Mexican technical NOMs and standardized measuring methods.

Air Pollutant Criteria	NOM	Publication Date	Description
SO_2	NOM-038-SEMARNAT-1993 [20]	18/10/1993	Equivalent method, UV fluorescence
CO	NOM-034-SEMARNAT-1993 [21]		Reference method, infrared absorption
NO_2	NOM-037-SEMARNAT-1993 [22]		Reference method, gas phase chemioluminiscence
O_3	NOM-036-SEMARNAT-1993 [23]		Equivalent method, UV photometry
PM_{10}	US EPA Equivalent method, [24]		Gravimetric or β-radiation attenuation
$PM_{2.5}$	US EPA Equivalent method, [24]		Gravimetric or β-radiation attenuation

Daily data of SO_2, CO, NO_2, O_3 and PM_{10} were obtained from monitoring stations of SIMA from 1 January 2016 to 31 December 2019. $PM_{2.5}$ was not considered in this study because all monitoring stations had both insufficient data and operational problems. The air quality data set was analyzed for each air pollutant according to the regulatory framework applicable in Mexico [15–19] in order to compare with the maximum permissible limit and determine the number of exceedances considering the specifications contained in these regulations for each pollutant. The integration times used for each air pollutant in order to determine the compliance with regulations were the following: mean 24 h for PM_{10}, 8-h moving average for O_3, 8-h mean and 24-h mean for SO_2, hourly data for NO_2, and 8-h moving average for CO. Air quality data from monitoring stations in Mexico with a good performance are integrated by SINAICA, applying strict quality controls and performing a validation process. However, sometimes, data obtained from SIMA monitoring stations were not continuous or in other cases, there were no records for a given pollutant. For this reason, to complete the data base, firstly, during the whole study period for each monitoring station, it was necessary to establish inclusion criteria to decide which stations would be included in the study and which would not. Secondly, if one station to be included showed missing data, it was necessary to apply an imputation method to complete the data. Criteria considered were the following:

Valid data percentage: In the estimations of mean concentrations for each air pollutant criterion, only monitoring stations showing values >75% of valid data were included. However, in the case of monitoring stations showing valid data >75% but also showing continuous missing data, it was necessary to apply an imputation method.

Missing data imputation: In the case of monitoring stations showing intermittent missing data, data bases were completed by applying NIPALS. The NIPALS (nonlinear iterative partial least squares) algorithm is a Jacobi-like iterative method used to estimate the elements of the principal component analysis of a finite dimensional random vector, commonly adapted for datasets with missing data. This imputation technique has been used by other authors to complete missing data [25–28]. On the other hand, if a given variable (pollutant or meteorological variable) from a monitoring station showed missing data in a sustained way during a long time period, data bases were completed by applying multiple and simple linear regressions with data of selected pollutants maintaining a significant relationship with this variable by using XLSTAT (http://www.xlstat.com/en/ accessed on 20 February 2020). To perform this selection, a statistical analysis of complete data including Pearson (bivariate) and PCA (multi-variate) was applied to identify the variable or group of variables related in a significant way with the pollutant showing missing data. Air quality was assessed by comparison with current national standards, and a Friedman test was applied to identify if there were significant differences in mean concentrations of air pollutant criteria among municipalities.

3.2. Epidemiologic Data

Studies relating exposure to air pollution and public health in developing countries are scarce. The main challenge is the collection of reliable data in both sectors, air quality and epidemiology. The main reason is the lack of economical support for data collection, resulting in a lack of coordination between the different government entities. At the same time, collection, storage, validation and computing processing of data are not continuous or uniform. Unlike air quality data (integrated information by SINAICA at national scale with free access), at this time, epidemiologic data have not been integrated at national scale. However, there is a system of health information (SINAIS, www.dgis.salud.gob.mx accessed on 19 March 2020) which has records of hospital admissions by state. This information is not freely accessible, however, for the purposes of this study, information was available during the study period. Morbidity or hospital admissions data were based on the international classification of diseases and health problems of the World Health Organization (WHO) rev CIE-10/2, considering specific causes (respiratory and circulatory). In addition, morbidity was studied by gender and by age group (<1 year, 1–4 years, 5–59 years, 60–74 years and >75 years).

3.3. Response, Explanatory and Confounding Variables

To perform statistical analysis of time series according to the methodology described by Cerón et al. [10] and Cerón et al. [11], the response variable was the number of daily hospital admissions for each municipality during the study period. It is important to emphasize that hospital admissions records are recorded by health institutions on a daily basis. For this reason, correlation analysis between time series of daily morbidity and current concentrations of air pollutant criteria was performed considering daily mean concentrations. It was according to a standard methodology established by APHEIS protocol. Explanatory variables were daily concentrations of CO, NO_2, O_3, SO_2 and PM_{10} for each municipality during the study period. Finally, daily average values for temperature and relative humidity were considered as confounding variables. In addition, some control variables were considered as seasonality indicator variables (seasonal strata): cold months and warm months.

3.4. Statistical Analysis and Association between Criteria Air Pollutants and Morbidity

To study the associations between variables, a PCA analysis was applied to the daily data series of morbidity, air pollutant criteria and meteorological variables. From this, the principal components contributing to the highest percentage of variability of data were identified. However, as a first step, it was necessary to carry out a pre-treatment of data series to know their dispersion, atypical data and their distribution. Time-series of epidemiologic data commonly show a variable variance, outliers and collinearity, among other limitations. Therefore, it was necessary to smooth time series by using non-parametric methods. LOWESS method (locally weighted regression scatterplot smoothing) was used in the case of epidemiologic data. In the case of air quality data, time series were smoothed by using ARIMA (autoregressive integrate moving average). Once time series were smoothed, the next step was to apply a Poisson model. A Poisson regression model was constructed as described by Ballester et al. [29], Ballester et al. [30] and Lowe et al. [31] according to standardized protocols proposed by APHEA (Air Pollution and Health, a European Approach) and EMECAM (Spanish Multicenter Study on Relationship between Atmospheric Pollution and Mortality) methodologies, to explain the fluctuations in morbidity with respect to explanatory and confounding variables.

In the first stage, a basal model was constructed obtaining an equation to determine relative risk index (RRI) as the magnitude of the association between morbidity and average daily levels of air pollutant criteria and meteorological variables, this methodology is the same as the used by [11]. The selected variables from PCA analysis were added to the basal model, considering a specific cause or all causes of hospital admission, gender and age group for each municipality. Since the effects of atmospheric pollution on morbidity are not immediate, it was necessary to include a lag term from an analysis of cross correlations for data series, selecting those lags showing major statistical significance ($p < 0.10$). In this case, meteorological variables were lagged by up to 7 days. The Poisson model relating the morbidity (response variable) with air pollutant criteria and meteorology variables (explanatory and confounding variables) is described by the following equation:

$$\ln E_y = \beta_o + \sum_{i=1}^{n} \beta_i X_{ij} \quad (1)$$

where E_y is the number of hospital admissions, X_{ij} the explanatory variables and βo and β_i the constants of the model. Once β coefficients are obtained, RRI can be estimated from:

$$RRI = e^{\beta_i} \quad (2)$$

where RRI is the relative risk index associated with the explanatory variable i per unit of increase of this variable, and β_i is the regression coefficient associated with the explanatory variable i in the model. In the second stage, a second scenario was constructed from the basal model, increasing the average concentrations of air pollutant criteria by 10% (one at a time, and keeping the remaining variables unchanged), obtaining new values of β coefficient and RRI for morbidity for all causes, respiratory and circulatory causes, considering gender and age group. This procedure was applied to data series of each municipality. Finally, with RRI values corresponding to each pollutant and each municipality, by using GIS, maps of relative risk indices were obtained for MAM during 2016–2019.

4. Results

4.1. Air Quality and Exceedances

In Table 3, mean concentrations for air pollutant criteria in each municipality during the study period are shown. It can be observed that the highest mean concentration for NO_2 was found in Santa Catarina; whereas, in the case of CO, the highest mean concentrations were found in Guadalupe and Cadereyta. In the case of O_3, Garcia showed the highest mean concentration; whereas, Cadereyta and Santa Catarina showed the highest mean concentration for SO_2. Finally, in the case of PM_{10}, it can be observed that García and Santa

Catarina showed the highest mean concentrations. In the municipality of Garcia, data for SO_2, CO and NO_2 were not available; whereas in Guadalupe data for NO_2 were not complete. SO_2 data in Monterrey were not sufficient. O_3 and PM_{10} were the only pollutants that had sufficient and complete data for all monitoring stations.

Table 3. Mean concentrations for air pollutant criteria in each municipality from 1 January 2016 to 31 December 2019.

Municipality	NO_2 (ppb)	CO (ppm)	O_3 (ppb)	SO_2 (ppb)	PM_{10} (µg m^{-3})
Cadereyta	12	1.1	24	7	63.9
Garcia	*	*	27	*	88.4
General Escobedo	15	0.8	25	5	74.9
Guadalupe	*	1.1	25	6	60.2
Monterrey	15	1.1	22	*	58.6
Salinas Victoria	14	0.9	25	5	58.7
San Nicolas de los Garza	13	1.0	23	5	74.0
Santa Catarina	18	0.8	25	7	81.2

* Data not available.

Air quality in MAM was assessed during 2016–2019 to identify if there were exceedances in air pollutant criteria concentrations or non-compliance with regulations (air quality standard or NOMs) in each municipality. Air pollutant concentrations vary spatially (there are differences associated with the geographic location and strength and location of emission sources), and they also vary temporally (hourly and seasonal variation), since some of these pollutants have a clear diurnal pattern or they are formed by photochemical reactions. The differences found among municipalities and among pollutants are due to these factors. The most important findings from this evaluation are summarized below.

Nitrogen dioxide (NO_2): Its maximum concentrations appear during the morning and decrease towards noon, increasing again during the nighttime. This is an inverse behavior to that of temperature and follows the pattern of vehicular traffic. The cold months are those that register the highest concentrations of this pollutant because the meteorological conditions favor the accumulation of gases in the Metropolitan Area of Monterrey, mainly in the downtown area. According to the emissions inventory for the Metropolitan Area of Monterrey [32], mobile sources are the second main contributor to the levels of NO_2 with 68% of the total emissions. For NO_2, it was found that there were no significant differences in the mean values of concentration at a level of significance of $\alpha = 0.05$ between the different studied municipalities (according to the Friedman hypothesis test), indicating that this air pollutant is homogenously distributed along the metropolitan area. The municipalities which showed the greatest mean concentrations for this pollutant during 2016–2019 were Santa Catarina, Monterrey and General Escobedo. These municipalities are characterized by having intense vehicular traffic, since important avenues and boulevards that cross the metropolitan area from east to west are located here. Monterrey is the main contributor to NOx emissions in the metropolitan zone (30.11%), with private vehicles and taxis, and the lime and cement industry, being the sources that contribute the most to NOx emissions with 38% and 16.8%, respectively [33]. None of the studied municipalities exceeded the maximum permissible limit established by [17]. The seasonality index for MAM was 1.97, suggesting that the highest concentrations occurred during winter months. Most municipalities showed a decreasing trend allowing compliance with the limits established in the regulation (Figure 2).

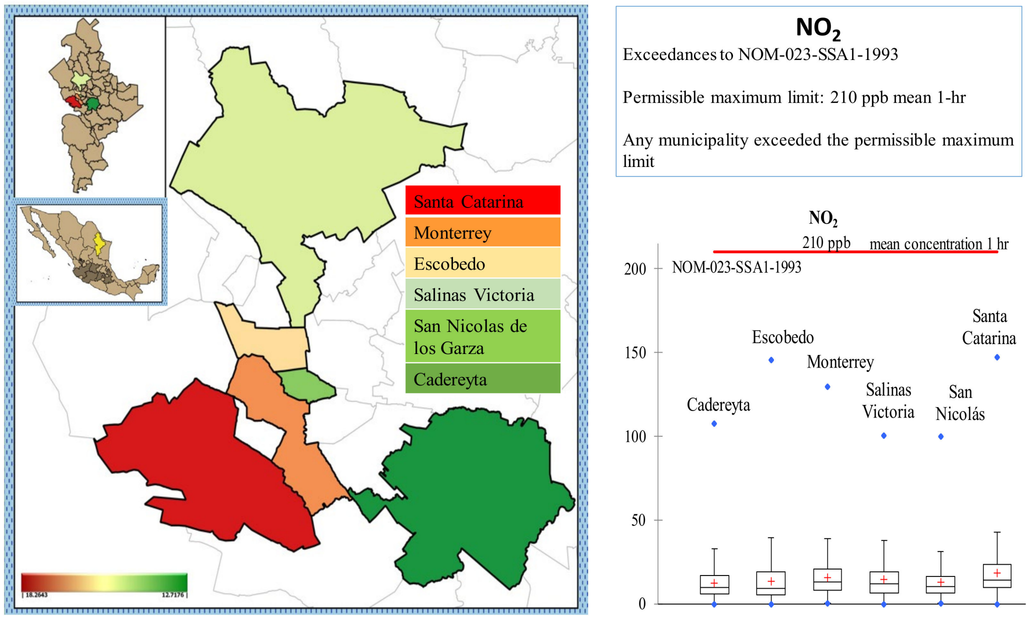


Figure 2. Mean concentrations of NO_2 in MAM during 2016–2019.

Carbon monoxide (CO): This air pollutant commonly presents higher concentrations during the winter months, registering its maximum concentrations during the first hours of the morning (from 6:00 a.m. to 9:00 a.m.), decreasing later throughout the day until 6:00 p.m., when its concentration levels increase again. Mobile sources are the main emission source of this pollutant, so that the maximum levels of CO coincide with the hours of greatest vehicular traffic. The increased concentrations during the winter months are mainly due to the poor dispersion of pollutants caused by weather conditions during these months. Municipalities which showed the highest mean concentration for CO in MAM during the study period were Guadalupe, Cadereyta, Monterrey and San Nicolas de los Garza. CO mean concentrations showed significant differences among municipalities at a level of significance of $\alpha = 0.05$ according to the Friedman hypothesis test. The high concentrations of CO are mainly due to a high degree of industrialization together with intense vehicular traffic, since there is important commercial and service activity in these municipalities. According to the emission inventory of air pollutant criteria for the Metropolitan Area of Monterrey [32], mobile sources are the primary contributor to CO emissions (96%), private cars and taxis being the main mobile sources contributing to the levels of this air pollutant. The main contributors to CO emissions in the metropolitan area are Monterrey and Guadalupe with 35.3% and 17.2% of the total emissions, respectively [33]. None of the studied municipalities exceeded the maximum permissible limit established by [16]. In this case, the seasonality index was 1.89, indicating that the highest concentrations were found during cold months. In general, except for Salinas Victoria, a decreasing trend in carbon monoxide levels in MAM was observed (Figure 3).

Ozone (O_3): This gas is a secondary pollutant that is formed by photochemical reactions involving nitrogen oxides and hydrocarbons. The daily behavior of this pollutant shows an elevation after noon, which coincides with the highest solar radiation, following a diurnal defined pattern. Ozone formation is affected by a large number of meteorological parameters, especially temperature and atmospheric stability. The eight municipalities studied had validated data for this pollutant, and in all of them, the maximum permissible limit established by [18] was exceeded a total of 2384 times, Garcia being the municipality which contributed the major proportion with 734 exceedances. O_3 mean concentrations did not show significant differences among municipalities at a level of significance of $\alpha = 0.05$ according to the Friedman hypothesis test.

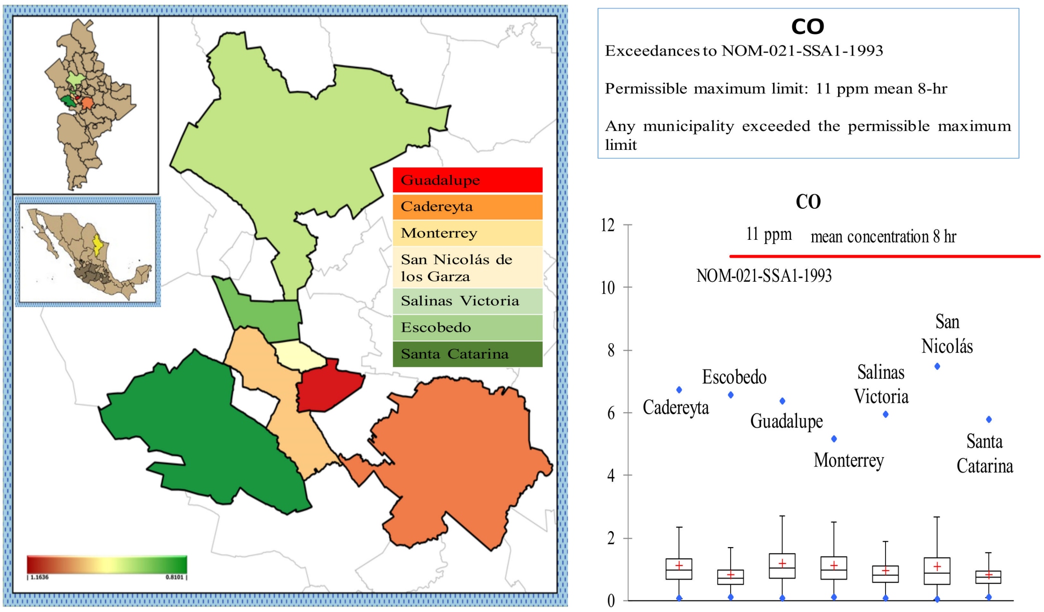


Figure 3. Mean concentrations of CO in MAM during 2016–2019.

The monitoring site in this municipality is located downwind from most industrial sources in García, in an area of high population concentration. The seasonality index in MAM for this pollutant was 0.70, suggesting that the highest concentrations of ozone occurred during the summer months. Most municipalities showed uniformity in ozone levels during the study period (Figure 4), probably because levels of its precursor (NO_2) are also homogenously distributed along the whole metropolitan area.

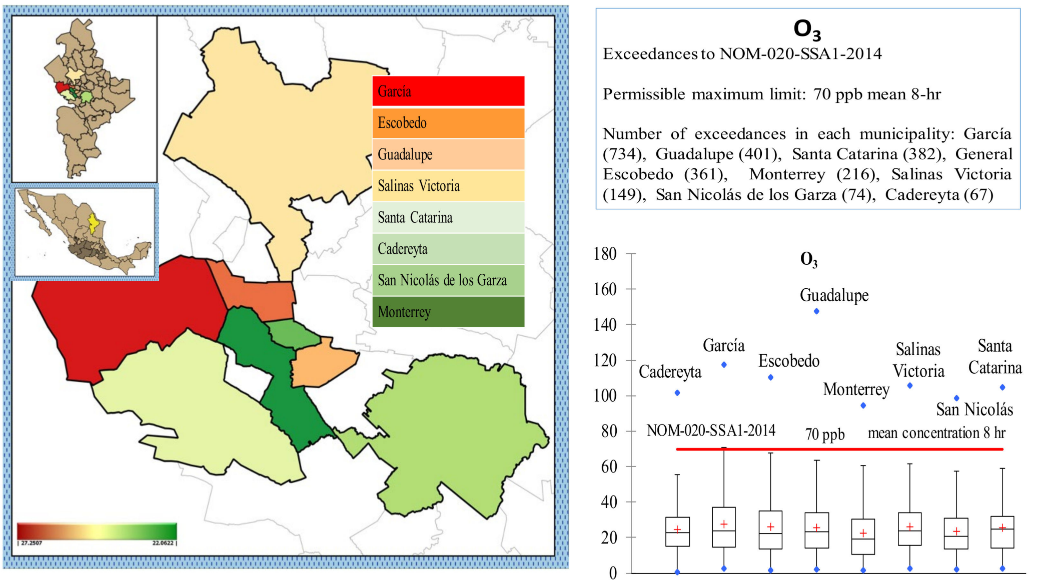


Figure 4. Mean concentrations of O_3 in MAM during 2016–2019.

Sulfur dioxide (SO_2): In the study area, this pollutant commonly presents its maximum concentrations from 7:00 a.m. to 4:00 p.m., which coincides with the period in which greater industrial activity and vehicular traffic is registered. The emissions of this pollutant come mainly from the oxidation of sulfur contained in fuels, mainly diesel and fuel oil, which is used in the combustion processes of a large number of industries. The highest concentrations of sulfur dioxide were detected during the warm months. This pollutant did not present exceedances above the maximum permissible level established by the air quality standard, but presented higher levels predominantly in the northeast area. The cause of the decrease in its levels in cold months is due to its water solubility, which causes it to be absorbed by moisture, and also its ability to react with suspended particles. According to the emissions inventory for the Metropolitan Area of Monterrey [32], fixed sources (industrial activity) are the main contributor to SO_2 emissions (97%). The most important fixed sources in this area are the oil and petrochemical industry, as well as electrical power generation and the metallurgical industry. SO_2 mean concentrations showed significant differences among municipalities at a level of significance of $\alpha = 0.05$ according to the Friedman hypothesis test. The highest mean concentrations of sulfur dioxide were found in Cadereyta and Santa Catarina, these municipalities are characterized by the presence of multiple and varied industrial facilities. Cadereyta is the main contributor to SO_2 emissions in the metropolitan area with 79.7% of the total emissions, with the oil and petroleum industry being the main source of emissions in this municipality [33]. None of the studied municipalities exceeded the maximum permissible limit established in [15]. The seasonality index was 1.305, indicating that the highest concentrations for this pollutant occurred during the winter season. Most municipalities showed a decreasing trend in annual and 24-h concentrations during the study period (Figure 5).

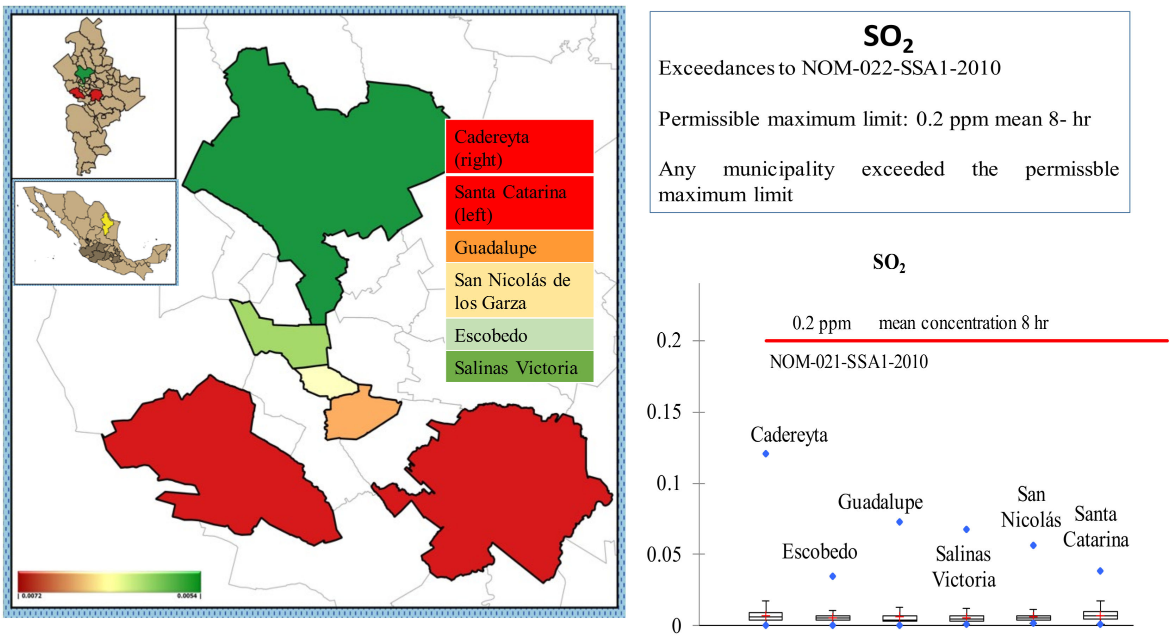


Figure 5. Mean concentrations of SO_2 in MAM during 2016–2019.

PM_{10}: In the study area, this air pollutant presents higher concentrations during the period from 8:00 a.m. to 4:00 p.m., which coincides with a greatest human and industrial activity. There is an increase of PM_{10} concentrations during the winter months because the weather conditions are not very favorable for the dispersion of pollutants. PM_{10} concentrations increase when the wind direction changes from the east (dominant direction) to a predominant one from the north-northwest. The cause of the increase in concentrations when the wind direction changes is mainly due to the impact of particle sources located west of the Monterrey metropolitan area. This pollutant usually exceeds the limits established in the air quality standard. The behavior of PM_{10} concentrations follows a pattern that marks a considerable increase during the months of winter and a notable decrease in spring and summer. This fact finds an explanation in the meteorological conditions that hinder the dispersion of pollutants during cold months, when thermal inversions are common. The main sources of particle emission, according to the latest inventory of emissions are industrial, vehicular sources and soil erosion. PM_{10} mean concentrations showed significant differences among municipalities at a level of significance of $\alpha = 0.05$ according to the Friedman hypothesis test. The municipalities showing the highest mean concentrations for PM_{10} were Garcia and Santa Catarina. The main source of PM_{10} in these municipalities are quarries and limestone extraction processes, followed by industrial and vehicular emissions [32]. Santa Catarina is the main contributor to PM_{10} emissions in the metropolitan area with 10.8% of the total emissions, the main sources, being extraction/benefit of non-metallic minerals and unpaved roads, contributing with 80% and 9.6%, respectively [33]. All municipalities had validated data for this pollutant and in all of them the maximum permissible level was exceeded [19] a total of 4054 times, Garcia being the municipality that contributed the major proportion with non-compliance (with 871 exceedances). The seasonality index for this pollutant was 1.23, suggesting that PM_{10} levels were higher during the cold months. All municipalities showed a uniform behavior in PM_{10} levels during the study period; however, some municipalities exhibited an increasing trend in their concentrations, such was the case for Guadalupe and Garcia (Figure 6).

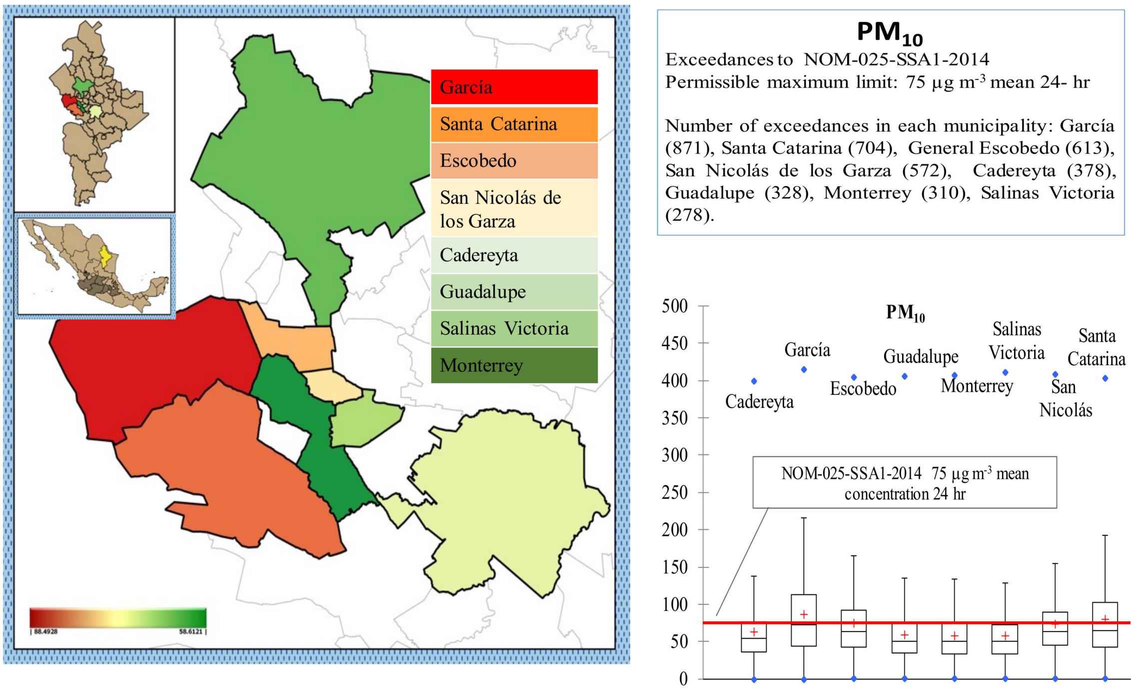


Figure 6. Mean concentrations of PM_{10} in MAM during 2016–2019.

4.2. Epidemiologic Study

Health data obtained from SINAIS was analyzed to identify trends and characterize morbidity behavior. Considering all causes (Figure 7), the highest number of hospital admissions was registered for people of both genders between 5 and 59 years, this number being higher for males; whereas the lowest morbidity was found for people older than 75 years. In the case of morbidity due to respiratory causes, it was higher during winter in the male population between 5 and 59 years; whereas for female individuals, the morbidity was higher in children under one year of age; in general, the number of hospital admissions for this specific cause was lower in people older than 60 years (Figure 8). Finally, in the case of morbidity due to circulatory causes, it showed extreme values in both cold and warm months, being more significant in the male population between 5 and 59 years; however, the number of hospital admissions for babies and infants of both genders was also high in comparison with the remaining population. The morbidity for people older than 60 years was the lowest for this specific cause (Figure 9).

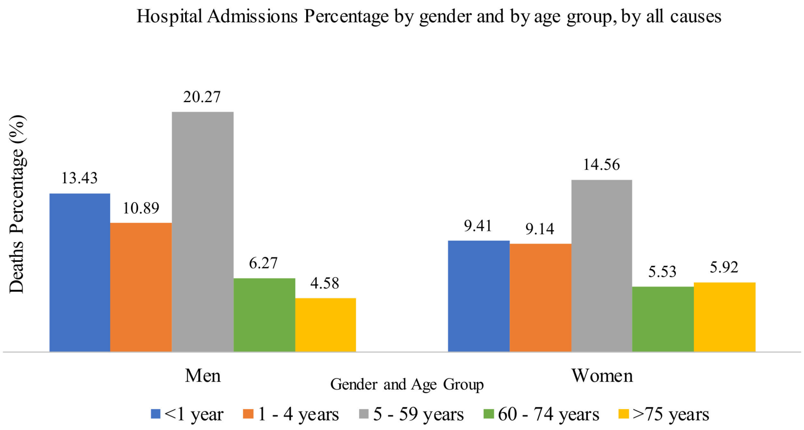


Figure 7. Hospital admission percentage by gender and age group for all causes.

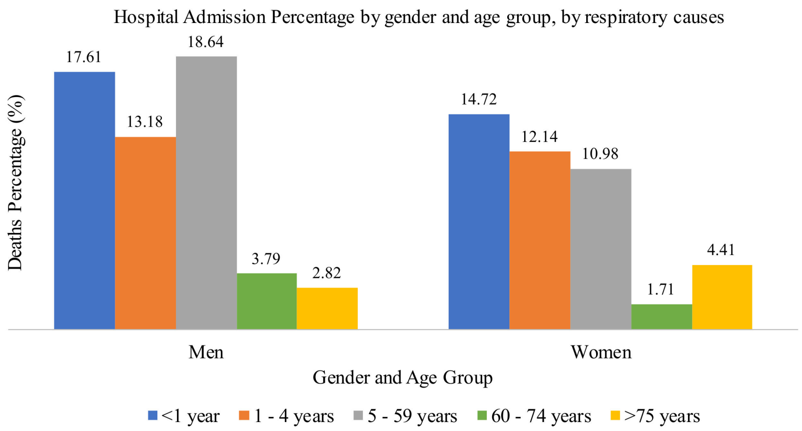


Figure 8. Hospital admission percentage by gender and age group for respiratory causes.

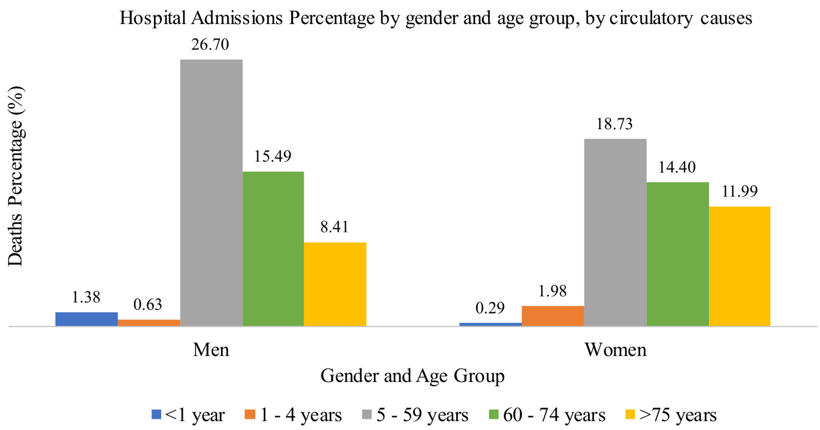


Figure 9. Hospital admission percentage by gender and age group for circulatory causes.

4.3. Statistical Analysis and Association between Criteria Air Pollutants and Morbidity

4.3.1. Analysis of Daily Morbidity Considering All Causes

From multiple linear regression, it was observed that Guadalupe, Monterrey and San Nicolás de los Garza showed the highest determination coefficients (R^2) considering all morbidity causes. This suggests that in these municipalities, explanatory variables (air pollutant criteria, relative humidity and temperature) explain the variability of response variable (morbidity) in 57.79%, 64.50% and 29.31%, respectively.

From Pearson correlation, multiple linear regression and Fisher tests, considering SO_2, it was found that none of the municipalities in MAM showed significant values; concluding that SO_2 does not provide significant information to the prediction model for daily morbidity. From the analysis of the association between CO and daily morbidity, Pearson correlation showed significant values only for Monterrey; whereas from the Fisher test, it was found that only Guadalupe provided significant information for the daily morbidity prediction model. From Pearson correlation, it was observed that only Monterrey and San Nicolás de los Garza showed significant values for NO_2; Fisher test demonstrated that NO_2 provided significant information to the prediction model of daily morbidity for Monterrey and San Nicolás de los Garza. The analysis of association between O_3 and daily morbidity considering bivariate relations showed significant information for Garcia, Monterrey and San Nicolas de los Garza; whereas from Fisher tests, it was found that O_3 provides significant information to the model for Guadalupe, Monterrey and San Nicolas de los Garza. Considering bivariate relations between PM_{10} and the number of hospital admissions, significant values were not found in MAM; from Fisher tests, it was found that this pollutant provided significant information to the model of daily morbidity only for Monterrey. From bivariate analysis, only Guadalupe showed significant values for relative humidity; from Fisher tests, it was found that this meteorological variable provided significant information to the daily morbidity model for Guadalupe and Monterrey. Finally, relations between temperature and daily morbidity were significant for Garcia, Guadalupe, Monterrey and San Nicolas de los Garza; from Fisher tests, it was found that this meteorological variable provided significant information to the model for Guadalupe, Monterrey and San Nicolas de los Garza.

In general, daily morbidity and CO, NO_2, O_3 and temperature were grouped into one principal component with a significant factorial load in Monterrey when all causes of hospital admissions were considered. On the other hand, PM_{10} was significantly associated with morbidity in Salinas Victoria.

4.3.2. Analysis of Daily Morbidity Considering Respiratory Causes

General Escobedo, Guadalupe and Monterrey showed the highest determination coefficients (R^2) in the multiple linear regression when respiratory causes were considered, indicating that in these municipalities, explanatory variables (air pollutant criteria, relative humidity and temperature) explain morbidity variability by 21.55%, 50.73% and 66.25%, respectively.

Bivariate analysis between SO_2 and daily morbidity showed significant values for General Escobedo and San Nicolas de los Garza; however, when Fisher test was applied, no significant correlation was found in any municipality. Considering bivariate correlations between CO and daily morbidity, only Monterrey showed significant values; on the other hand, when Fisher test was applied, CO does not provide significant information for any municipality. From Pearson correlation, significant values were found between morbidity and NO_2 in General Escobedo, Monterrey and San Nicolas de los Garza; whereas from Fisher tests it was found that NO_2 provides significant information to the daily prediction model in Monterrey. In the case of O_3, significant bivariate correlations were found in Garcia, General Escobedo, Guadalupe, Monterrey and San Nicolas de los Garza; according to Fisher tests, O_3 only provided significant information for the model for Guadalupe. Considering bivariate analysis between PM_{10} and daily morbidity, no significant association was found in MAM, with Monterrey being the only municipality in which PM_{10} provided significant information to the morbidity model according to Fisher test. Relative humidity only showed significant values in the bivariate analysis for Guadalupe; from Fisher test, Guadalupe and Monterrey were the only municipalities in which this variable provided significant information to the model. Considering temperature, from bivariate correlation, significant values were found in Garcia, General Escobedo, Guadalupe, Monterrey, Salinas Victoria and San Nicolas de los Garza. From Fisher tests, it was found that Monterrey and

Guadalupe were the only municipalities in which this meteorological variable provided significant information to the daily morbidity prediction model.

In general, daily morbidity, CO, NO_2, O_3 and temperature were grouped in one principal component with a significant factorial load in Monterrey, when respiratory causes were considered. In addition, relative humidity was also grouped with hospital admissions in Guadalupe.

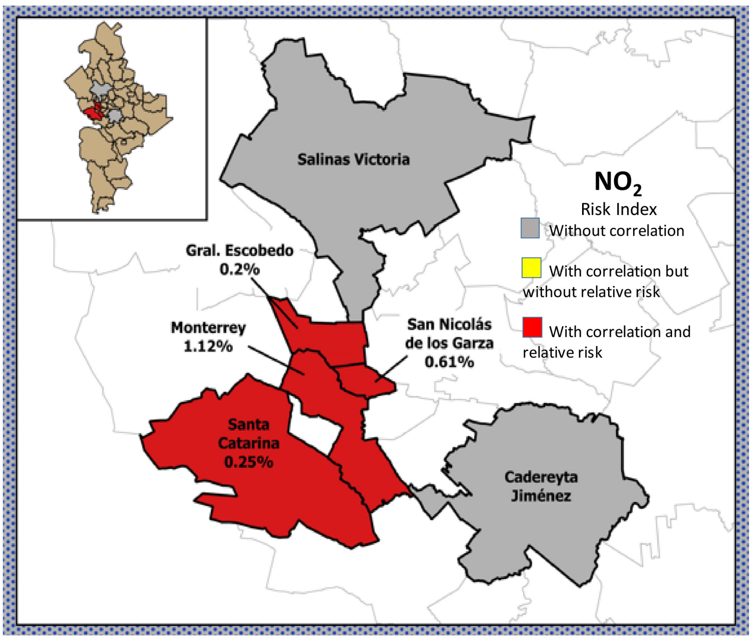
4.3.3. Analysis of Daily Morbidity Considering Circulatory Causes

Cadereyta and Santa Catarina, showed the highest determination coefficients (R^2) in the multiple linear regression when circulatory causes were considered, suggesting that explanatory variables (air pollutant criteria and meteorological variables) contributed 11.88% and 33.79% towards explaining the variability of morbidity. Except for NO_2, bivariate correlations between SO_2, CO, O_3, PM_{10}, relative humidity, temperature and daily morbidity showed significant values in MAM for any municipality, the same was found when Fisher test was applied. From Pearson analysis, the highest correlations between NO_2 and the number of hospital admissions were found in San Nicolas de los Garza and Santa Catarina; however, when Fisher test was applied, it was found that NO_2 provides significant information to the morbidity model for any municipality. Since there was no correlation between meteorological variables, pollutants and daily morbidity, any variable was grouped in a principal component with a significant factorial load.

4.3.4. Relative Risk Index and Comparison with Other Studies

The only age group which showed a significant association between NO_2 levels and daily morbidity was 5–59 years; the highest relative risk indexes (RRI) were found during the cold months for this age group when all causes were considered.

From Table 4, it can be observed that RRI values in municipalities of MAM were very similar to each other. RRI values in MAM were higher than those reported for Central China, but lower than those found in Mexico City [34], India [35], New Zealand [36], higher than those found in Canada [37] and, Iran [38], and higher than values reported for Chengdu, China [39], Thailand [40] and Korea [41–46]. From Figure 10, it can be observed that when daily mean NO_2 levels increased by 10%, the number of daily hospital admissions increased in Monterrey (1.12%) and San Nicolas de los Garza (0.61%).



Municipality	RRI (CI)
Cadereyta	-
General Escobedo	1.0020 (0.9899 - 1.01449
Monterrey	1.0112 (0.9974 - 1.0253)
Salinas Victoria	-
San Nicolás de los Garza	1.0061 (0.9925 - 1.0201)
Santa Catarina	1.0025 (0.9889 - 1.0164)

Figure 10. Relative risk indexes in MAM for the hypothetical scenario in which daily mean concentrations for NO_2 increased by 10%, considering all causes.

Table 4. RRI, lower and upper limit values found in MAM for NO_2 during the study period, and comparison with values reported by other studies around the world.

Site	LL	RRI	UL	Cause
Mexico City [34]	1.1468	1.2125	1.2782	Respiratory, Children
India [35]	0.99	1.021	1.06	All, adults
New Zealand [36]	1.09	1.18	1.28	Respiratory, Children
Canada [37]	0.983	0.991	0.999	Respiratory
Isfahan, Iran [38]	1.0004	1.0038	1.0094	Respiratory
Isfahan, Iran [38]	1.0015	1.0036	1.0084	Circulatory
Chengdu, China [39]	1.37	3.48	5.64	Respiratory
Central China [6]	0.06	0.52	0.99	All
Thailand [40]	0.94	1.01	1.09	Circulatory
Seoul, Korea [41]	1.1	1.15	1.2	Respiratory
Seoul, Korea [42]	1.06	1.18	1.31	Respiratory
Seoul, Korea [43]	0.6	2.2	3.7	Respiratory
Seoul, Korea [43]	1.1	2.2	3.4	Circulatory
Seoul, Korea [44]	1.03	1.67	2.71	Respiratory
Seoul, Korea [45]	0.994	1.073	1.157	Respiratory
Seoul, Korea [45]	0.968	1.047	1.134	Circulatory
Seoul, Korea [46]	1.46	1.81	2.25	Circulatory
Seoul, Korea [46]	2.29	2.65	3.06	Respiratory
General Escobedo	0.9899	1.0021	1.0144	All
Monterrey	0.9974	1.0112	1.0253	All
San Nicolás de los Garza	0.9925	1.0062	1.0201	All
Santa Catarina	0.9889	1.0026	1.0164	All
Cadereyta	0.9625	0.9964	1.0316	5–59 years
Escobedo	0.9874	1.0007	1.0142	5–59 years
Monterrey	1.0017	1.0081	1.0144	5–59 years
Salinas Victoria	0.8865	1.0063	1.1424	5–59 years
San Nicolás de los Garza	0.9862	1.003	1.0201	5–59 years
Escobedo	0.9869	1.0024	1.018	Respiratory
Monterrey	1.0019	1.0087	1.0155	Respiratory
San Nicolás de los Garza	0.9808	1.001	1.0216	Respiratory
Santa Catarina	0.9876	1.0018	1.0161	Respiratory
San Nicolás de los Garza	0.988	1.0043	1.0208	Circulatory
Santa Catarina	0.9838	1.0082	1.0333	Circulatory

The only age group that showed a significant association between CO daily mean concentrations and daily hospital admissions was 5–59 years; and the highest RRIs were also found for this population group, considering all causes. From Table 5, it can be observed that RRI values found in all municipalities of MAM were very similar to each other, and lower than those reported for Thailand [40] and Korea [41–46]. Monterrey was the only municipality that showed a significant value for RRI (0.001%) as a result of a hypothetical scenario in which its daily mean concentration increases by 10% (Figure 11).

Table 5. RRI, lower and upper limit values found in MAM for CO during the study period, and comparison with values reported by other studies around the world.

Site	LL	RRI	UL	Cause
Thailand [40]	1	1.07	1.15	Circulatory
Seoul, Korea [41]	1.1	1.16	2.22	Respiratory
Seoul, Korea [42]	1.02	1.16	1.32	Respiratory
Seoul, Korea [44]	1.03	1.1	1.19	Respiratory
Seoul, Korea [45]	0.987	1.336	2.011	Respiratory
Seoul, Korea [46]	1.72	2.12	2.611	Circulatory
Seoul, Korea [46]	1.73	2	2.3	Respiratory
Guadalupe	0.9999	0.9999	1	All
Monterrey	0.9998	1	1.0021	All
San Nicolás de los Garza	0.9998	1	1.0001	All
Santa Catarina	0.9995	0.9999	1.0003	All
Cadereyta	0.9997	1.0001	1.0005	5–59 years
Guadalupe	0.9997	0.9999	1.0002	5–59 years
San Nicolás de los Garza	0.9998	1	1.0002	5–59 years
Santa Catarina	0.9996	0.9999	1.0003	5–59 years
Escobedo	0.9995	0.9999	1.0003	Respiratory
Guadalupe	0.9997	0.9999	1.0002	Respiratory
Monterrey	0.9999	1	1.0001	Respiratory
San Nicolás de los Garza	0.9998	1	1.0002	Respiratory
Santa Catarina	0.9995	0.9999	1.0004	Respiratory

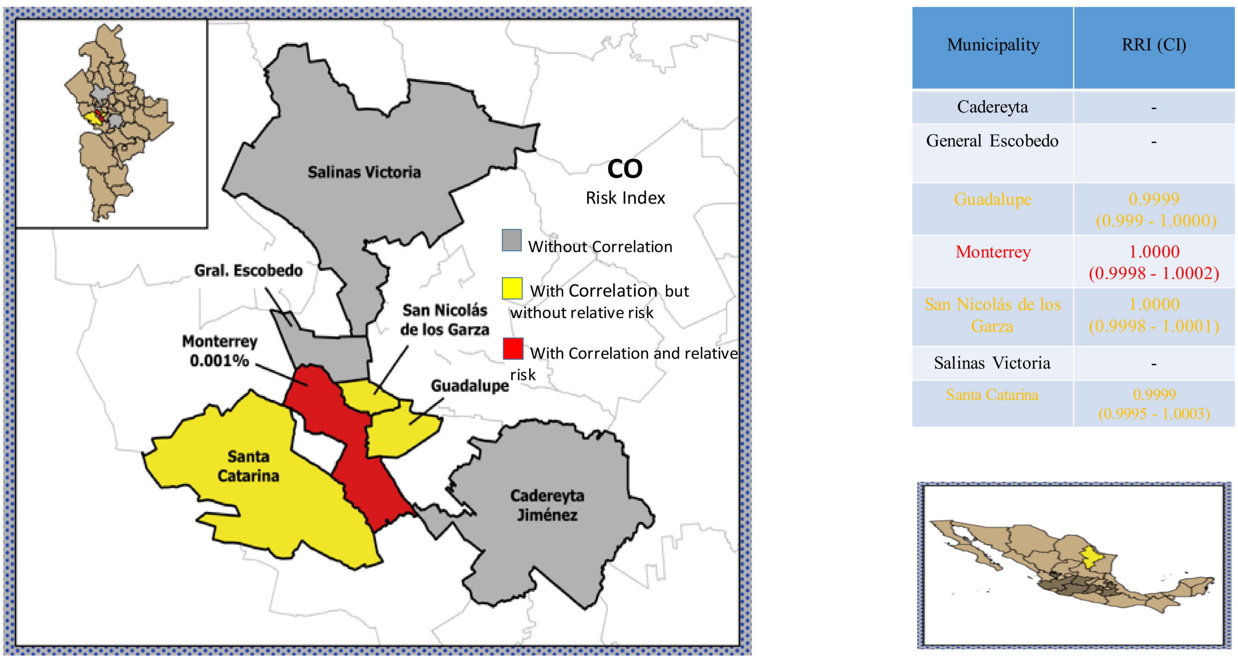


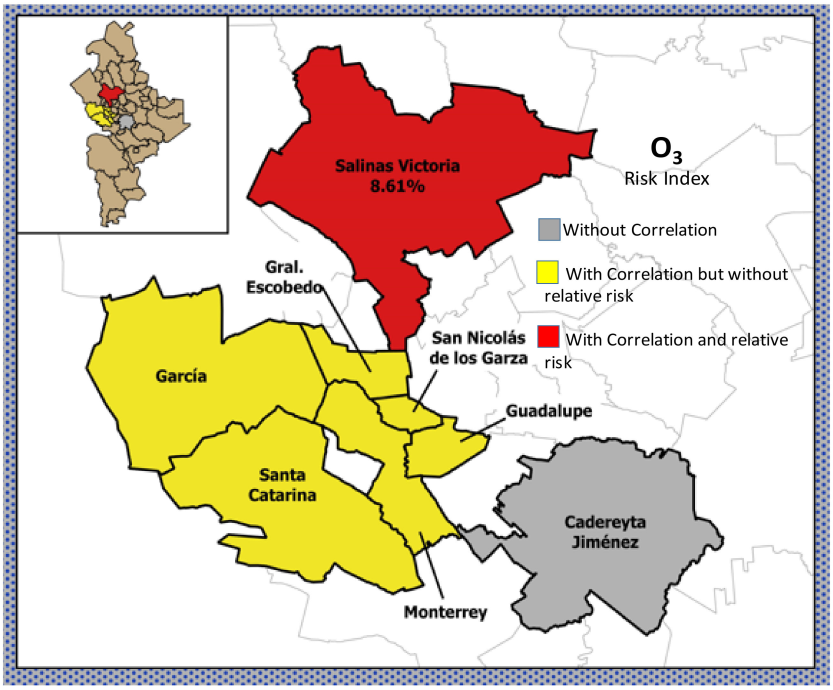
Figure 11. Relative risk indexes in MAM for the hypothetical scenario in which daily mean concentrations for CO increased by 10%, considering all causes.

The only age group which showed a significant association between O_3 levels and daily morbidity was 5–59 years.

From Table 6, it can be observed that RRI values found in all municipalities of MAM were very similar to each other, except Salinas Victoria, which showed values higher than most of the municipalities. In addition, RRI values found in MAM were comparable with those reported for USA [47], Mexico City [34] and Canada [37], and lower than those found in Korea [41,46]. The highest relative risk indexes as a result of the exposure to ozone considering all causes were found in Salinas Victoria. In spite of this, ozone showed the greatest number of exceedances to regulation, when daily epidemiological data were correlated with an increase of 10% in its daily mean concentrations; relative risk indexes were not significant for most of the municipalities, except for Salinas Victoria, where an increase of 8.61% was estimated (Figure 12).

Table 6. RRI, lower and upper limit values found in MAM for O_3 during the study period, and comparison with values reported by other studies around the world.

Site	LL	RRI	UL	Cause
Juárez City, Mexico [9]	1.021	1.051	1.085	Respiratory, children
Mexico City [34]	1.0339	1.0472	1.0603	Respiratory, children
Canada [37]	1.036	1.043	1.051	Respiratory
Seoul, Korea [41]	1.07	1.12	1.16	Respiratory
Seoul, Korea [46]	0.63	0.71	0.82	Circulatory
Seoul, Korea [46]	0.55	0.6	0.65	Respiratory
Ohio, USA [47]	1.02	1.09	1.16	All, adults
García	0.9625	0.9989	1.0366	All
Escobedo	0.9886	0.9995	1.0105	All
Guadalupe	0.9863	0.9929	0.9995	All
Monterrey	0.9833	0.9979	1.0127	All
Salinas Victoria	0.956	1.0861	1.2339	All
San Nicolás de los Garza	0.986	0.9974	1.0089	Al
Santa Catarina	0.9796	0.9964	1.0134	All
Cadereyta	0.9758	0.9991	1.0228	5–59 years
García	0.9723	0.9984	1.0253	5–59 years
Guadalupe	0.9754	0.9932	1.0114	5–59 years
San Nicolás de los Garza	0.9823	0.9963	1.0104	5–59 years
Santa Catarina	0.9799	0.999	1.0185	5–59 years
García	0.9526	1.0015	1.0528	Respiratory
Escobedo	0.983	0.9972	1.0116	Respiratory
Guadalupe	0.9732	0.9912	1.0095	Respiratory
Monterrey	0.9915	0.9987	1.0059	Respiratory
San Nicolás de los Garza	0.9825	0.9975	1.0127	Respiratory
San Nicolás de los Garza	0.986	0.9974	1.0089	all
Santa Catarina	0.981	0.9968	1.0127	Respiratory



Municipality	RRI (CI)
Cadereyta	-
García	0.9989 (0.9625 - 1.0366)
General Escobedo	0.9995 (0.9886 - 1.0105)
Guadalupe	0.9929 (0.9863 - 0.9995)
Monterrey	0.9979 (0.9833 - 1.0127)
Salinas Victoria	1.0861 (0.9560 - 1.2339)
San Nicolás de los Garza	0.9974 (0.9860 - 1.0089)
Santa Catarina	0.9964 (0.9796 - 1.0134)

Figure 12. Relative risk indexes in MAM for the hypothetical scenario in which daily mean concentrations for O_3 increased by 10%, considering all causes.

The only age group which showed a significant association between SO_2 daily mean concentrations and daily number of hospital admissions was 5–59 years; the highest RRIs for this age group were also found in Salinas Victoria.

Table 7 shows RRI values found in MAM for SO_2 and a comparison with other studies around the world. It can be observed that RRI values found in all municipalities of MAM were very similar to each other, except Salinas Victoria, which showed values higher than most of the municipalities when the age group between 5 and 59 years was considered. In addition, RRI values found in MAM were comparable with those reported for Iran [38], lower than those values found in Thailand [40], comparable with the results reported for Korea [41,42,44], lower than those found in Seoul during 2017 [46]; and comparable with values reported in USA [47].

From Figure 13, it can be observed that when SO_2 daily mean concentrations were increased by 10%, only Guadalupe showed an increase in the number of hospital admissions (0.28%).

The only age group which showed a significant association between PM_{10} daily mean concentrations and daily number of hospital admissions was 5–59 years; showing the highest relative risk indexes for this population group during the cold months.

From Table 8, it can be observed that RRI values found in all municipalities of MAM were very similar to each other, and comparable with those reported in Juarez City [9], lower than those found in China [39], Korea [41,43], USA [47] and Korea [48], comparable with those values reported for European cities [49,50], but lower than those found in Iran [51] and Korea [52]. When a hypothetical scenario was considered in which PM_{10} daily mean levels increased by 10%, Salinas Victoria (0.04%) and Guadalupe (0.09%) were the only municipalities which showed an increase in the number of hospital admissions (Figure 14).

Table 7. RRI, lower and upper limit values found in MAM for SO_2 during the study period, and comparison with values reported by other studies around the world.

Site	LL	RRI	UL	Cause
Isfahan, Iran [38]	1	1.004	1.011	Respiratory
Isfahan, Iran [38]	1.0026	1.0064	1.01	Circulatory
Thailand [40]	1.08	1.22	1.38	Circulatory
Seoul, Korea [41]	1.06	1.11	1.17	Respiratory
Seoul, Korea [42]	1.01	1.12	1.25	Respiratory
Seoul, Korea [44]	1.01	1.09	1.17	Respiratory
Seoul, Korea [46]	1.52	1.82	2.19	Circulatory
Seoul, Korea [46]	2	2.25	2.54	Respiratory
Ohio, USA [47]	0.99	1.03	1.06	All, adults
Cadereyta	0.9486	0.9937	1.0408	All
Guadalupe	0.9937	1.0029	1.0122	All
Cadereyta	0.9293	0.9862	1.053	5–59 years
Escobedo	0.9508	0.9994	1.0506	5–59 years
Salinas Victoria	0.7709	1.105	1.5838	5–59 years
Escobedo	0.9588	1.0114	1.0668	Respiratory
San Nicolás de los Garza	0.9678	1.0065	1.0469	Respiratory

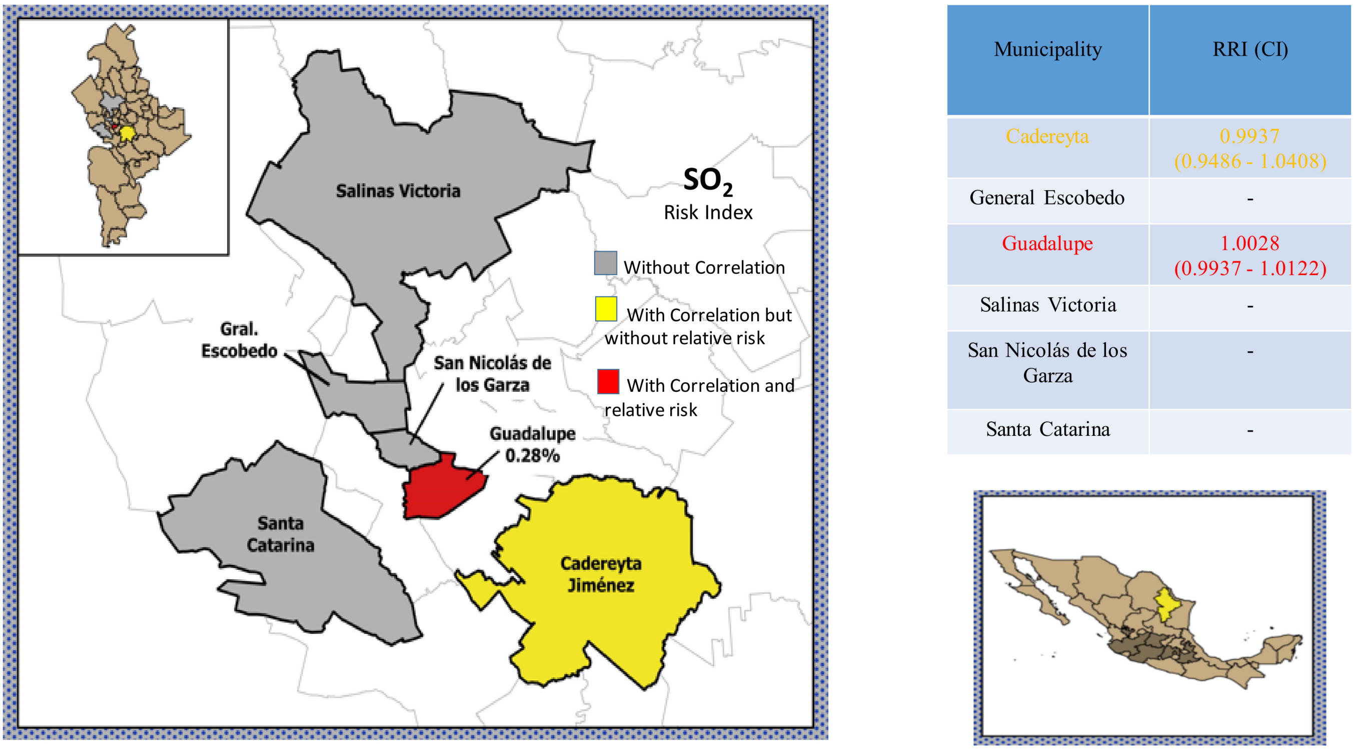


Figure 13. Relative risk indexes in MAM for the hypothetical scenario in which daily mean concentrations for SO_2 increased by 10%, considering all causes.

Table 8. RRI, lower and upper limit values found in MAM for PM_{10} during the study period, and comparison with values reported by other studies around the world.

Author	LL	IRR	UL	Cause
Juárez City, Mexico [9]	0.981	1.004	1.028	all, children
Juárez City, Mexico [9]	0.975	1.002	1.03	Respiratory, children
Juárez City, Mexico [9]	0.979	1.01	1.042	Circulatory, children
Chengdu, China [39]	0.75	1.31	1.8	Respiratory
Thailand [40]	1.04	1.13	1.23	Circulatory
Seoul, Korea [41]	1.04	1.07	1.11	Respiratory
Seoul, Korea [43]	0.9	1.7	2.6	Respiratory
Ohio. USA [47]	1.01	1.12	1.24	all, adults
Seoul, Korea [48]	1.02	1.09	1.15	Circulatory
8 European cities [49]	1.003	1.006	1.009	Circulatory
European Cities [50]	1.006	1.011	1.0017	Respiratory
Iran [51]	1.04	1.117	1.189	All, adults
Iran [51]	0.98	1.08	1.19	All. Children
14 cities, USA [53]	1.01	1.17	1.33	Circulatory
14 cities, USA [53]	1.49	1.98	2.47	Respiratory
Seoul, Korea [52]	0.94	1.19	1.44	Respiratory
Escobedo	0.9956	0.991	1.0026	All
Guadalupe	0.9991	1.001	1.0028	All
Monterrey	0.9938	0.9983	1.0029	All
Salinas Victoria	0.9474	1.0005	1.0565	5–59 years
Cadereyta	0.9938	1.0007	1.0076	5–59 years
Guadalupe	0.9967	1.0017	1.0067	5–59 years
Monterrey	0.9968	0.9988	1.0008	5–59 years
Guadalupe	0.9961	1.0012	1.0064	Respiratory
Monterrey	0.9969	0.9991	1.0014	Respiratory
San Nicolás de los Garza	0.9961	1.0008	1.0054	Respiratory
Santa Catarina	0.9861	0.9974	1.0088	Circulatory

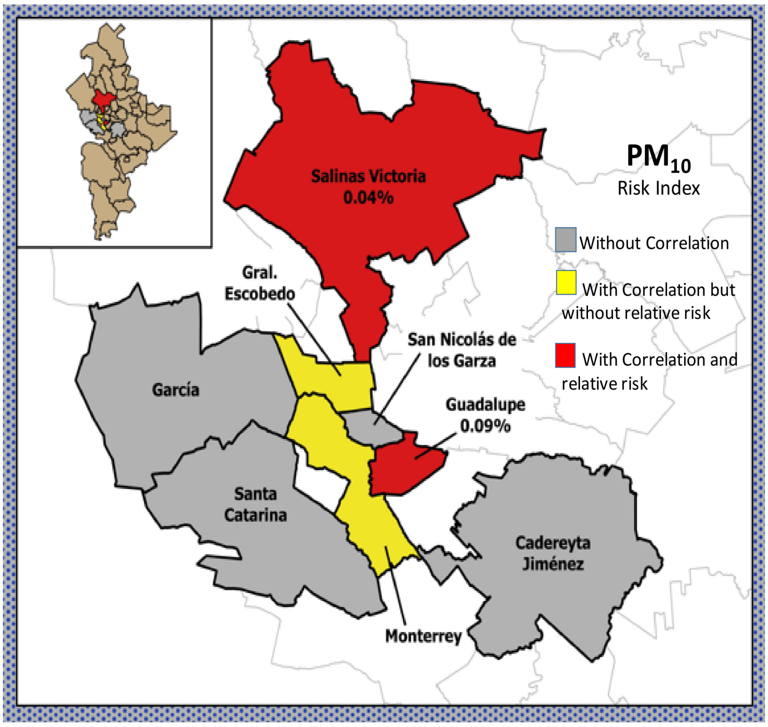
4.4. Discussion

Some aspects that deserve to be discussed separately, related to the strengths and weaknesses of this study, have been identified.

4.4.1. Exposure Data

Regarding exposure data, despite the need to measure $PM_{2.5}$ atmospheric particulates, only two municipalities in MAM had validated data for this pollutant. It is necessary to improve the operational functions and the performance of monitoring stations to ensure the availability of representative and sufficient data for this pollutant.

In this study, a design of temporal series was used for each municipality to assess the short-term associations between daily mean concentrations of air pollutant criteria and daily morbidity. However, this kind of approach has some limitations, since it only allows assessing of the acute impact of atmospheric pollution. Regarding the findings of the present study, particularly in the case of ozone, despite presenting the largest number of exceedances to permissible maximum limit established in the regulation, this pollutant did not show a significant correlation with daily morbidity for all municipalities in MAM. This fact suggests that ozone's health effects are long-term, therefore, this study recommends assessing the long-term effects of this pollutant, by using cohort studies. Regarding this, Wilmshurt [54] demonstrated that lung damage as a result of exposure to ozone is a cumulative effect, for this reason, short-term studies did not report a significant relationship between ozone levels and health effects. This would explain the lack of association and the low statistical significance found for this pollutant in this study.



Municipality	RRI (CI)
Cadereyta	-
García	-
General Escobedo	0.9991 (0.9956 - 1.0026)
Guadalupe	1.0009 (0.9991 - 1.0028)
Monterrey	0.9983 (0.9938 - 1.0029)
Salinas Victoria	1.0004 (0.9474 - 1.0565)
San Nicolás de los Garza	-
Santa Catarina	-

Figure 14. Relative risk indexes in MAM for the hypothetical scenario in which daily mean concentrations for PM_{10} increased by 10%, considering all causes.

SO_2, CO and PM_{10} showed the largest magnitudes of RRIs, however, the largest exceedances of maximum permissible limits occurred for ozone. It can be explained considering the temporality of ozone concentration peaks, reducing the exposure time to a few hours a day, when solar radiation is intense and photochemical activity is high (at midday). In addition, this time period coincides with when people whose activities are developed indoors stay in their offices and schools. At the same time, exceedances are estimated as a function of the maximum values of mean concentrations in a time period; whereas, correlation analysis between time series of morbidity and air pollutant criteria are estimated considering daily mean concentrations in a time period.

4.4.2. Health Data

Even when it is known that ozone exposure may cause symptoms, such as eyes, nose and throat irritation, nasal discharge, and so on, in a short term, most people do not go to health institutions. For this reason, this kind of morbidity is not registered in the national health system. A fundamental problem in Mexico is that health services are offered by disarticulated subsystems which offer different levels of attention at different prices, with different effectiveness and whose access is conditional according to employment situation. As a result of this, people sometimes go to generic health services, whose statistics are not included in the SINAIS registers. According to OCDE (2016), a large percentage of people in Mexico do not have access to health services from the state (approximately 18% of the total population of Mexico), this could under estimate the number of hospital admissions registered by SINAIS, thus losing representativeness. This is the mean reason for the lack of coordination between different health institutions in Mexico, and as a result of this, the lack of integrated morbidity data.

4.4.3. Association between Morbidity and Criteria Air Pollutants

A short-term positive correlation between air pollution and morbidity was found in this study, however, despite the magnitude of associations found being relatively low, its implications in the field of public health can be significant, considering the total number of people exposed and the need to establish control measures.

4.4.4. Seasonality

A clear seasonal behavior was observed, morbidity was higher during the winter; and SO_2, CO, NO_2 and PM_{10} showed the highest concentrations during the cold months. On the other hand, during the summer, when solar radiation is higher (promoting photochemical activity and atmospheric reactions to produce tropospheric ozone), ozone concentrations were higher. However, although this seasonal pattern occurred in all municipalities, the association between morbidity and temperature and its magnitude depend on other factors, such as population characteristics (sociodemographic structure and housing conditions), health service and study zone.

4.4.5. Population Characteristics

The variability of obtained parameters from adjusted models depends on the population size and the study period. Regarding the former, the number of inhabitants among municipalities showed great variability, it produced unstable estimates as causes were disaggregated by specific cause, this is probably the main reason why significant correlations were not found when respiratory and circulatory causes were considered. Regarding the study period, data availability reduced the study period to four years, making it more difficult to obtain results with statistical significance, obtaining relatively low magnitudes. However, updated information has some advantages, since the impact of air pollution on morbidity is closer to current conditions; at the same time, when relatively short time periods are considered, the characteristics of the population do not change much (age, occupation, routines, exposure, habits, socioeconomic status, and so on), making the study more representative.

The age group which showed the highest risk of morbidity associated to an increase in air pollutants concentrations was between 5 and 59 years. This population range constitutes the economically active population and students, which in turn comprises the majority of the population. It could explain the highest RRIs found for this age group, since given the nature of their activities, this sector of population has a greater mobility and are exposed for longer.

4.4.6. Housing Conditions and Study Zone

It has been reported that the isolation of houses is associated with a minor morbidity [55,56]. At the same time, housing conditions are related to socioeconomic conditions, being a conditional factor for the association between temperature, pollution and morbidity. In addition, the location of houses around sources of atmospheric pollution, topography, local meteorology and urban and industrial development also define the level of exposure of people.

4.4.7. Exposure Assessment

In this study, the same exposure of the entire population residing in a municipality, without considering the area in which they carry out their daily activities, daily routines and the hours in which they stay exposed indoors and outdoors, was assigned. For this reason, it is necessary to consider routines and habits of the studied population. Most of the studied municipalities have a temperate climate, for this reason, hospitals, workplaces, offices, schools, homes, and so on, do not have insulation. In addition, according to

Rojas-Bracho [57] and Fernandez-Bremauntz [58], people in Mexico stay indoors for longer periods, approximately 20 h indoors, 2.76 h outdoors, and 1.22 h when commuting to the city. Regarding this, this study did not include information about individual activity or personal exposure.

5. Conclusions

The results found here were consistent with studies carried out in other countries. The air pollutant criteria which showed the highest RRI values for daily morbidity as a result of an increase of 10% in daily mean concentrations were SO_2, NO_2, O_3 and PM_{10}. Regarding seasonality, all pollutants studied, except O_3, showed higher concentrations during the winter months. Considering the age group by all causes, most of the pollutants and municipalities studied showed a significant number of associations between daily mean concentrations and daily number of hospital admissions; and the magnitude was more significant for the age subgroup between 5 and 59 years, suggesting that this group of the population could be more vulnerable to the effects derived from atmospheric pollution.

In general, associations found in MAM did not show a trend by specific cause, since, hospital admissions due to circulatory diseases showed the same significance as those due to respiratory diseases. During the cold months, the association between morbidity and air pollutants was higher than during warm months in both circulatory and respiratory diseases.

The age group which showed the highest risk of morbidity associated with an increase in air pollutant concentrations (5–59 years) constitutes the economically active population and students, since given the nature of their activities, this sector of population has a greater mobility and remain exposed for longer. Therefore, results found in this study can be used by decision makers to develop public policies focused on protecting vulnerable populations.

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