Original Research Article

EVOLUTION OF AIR POLLUTION IN THE MONTERREY METROPOLITAN AREA, MEXICO

ABSTRACT

The Monterrey Metropolitan Area (MMA) is considered the second most populated metropolis in Mexico, with around 5,341,171 inhabitants, making it necessary to maintain a constant rate of growth of urban services which has caused it to be one of the cities with the greatest increase in air pollution rates in recent years as a result of human activities. Likewise, the MMA is located in a place with diverse natural formations that extend throughout the city, receiving the nickname of the "City of the mountains". These formations together with the polluting emissions product of various sources such as industries, vehicles, natural phenomena; and weather conditions, considerably increase the concentrations of pollutants that impact the quality of life of living beings. **Objective**: The objective of this research is to show the evolution of air pollution in the first two decades of this century, evaluate its trend and highlight the risks to which urban inhabitants and ecosystems are subjected. **Materials and method**: Data from the Environmental Monitoring Integral System (SIMA) of the Ministry of Environment of the Government of the State of Nuevo León, which has 14 monitoring stations of criteria pollutants, were used to evaluate the evolution and distribution of air pollution in the MMA. Concentrations of CO, NO_2, SO_2, PM_{10}, $PM_{2.5}$ and O_3 were evaluated. The trend of the hourly, daily, monthly and annual time series was evaluated to see patterns and the distribution of pollutants in the MMA have changed during the last years. **Results**: The results show that the pollutants have a great variability and these are based on multiple natural factors (thermal inversion, wind speed and direction, orography, among others) and/or anthropogenic factors (mobility, agricultural, industrial, services, fires, among others). They also depend on the time of year with an increase in particulate matter in the dry season and ozone in the wet season. **Conclusions**: The criteria pollutants that recorded the highest number of days out of the norm and with the greatest tendency to increase during the last two decades are PM_{10}, O_3 and $PM_{2.5}$, which represents a risk to environmental and human health. The pollutants CO, NO_2, SO_2, so far do not represent a risk to the population, since these are within the norm both for the number of days and for the daily, annual and monthly averages.

***Key words**: Criteria contaminants, Monterrey Metropolitan Area, environmental and health risks.*

1. INTRODUCTION.

The evolution, growth and development of urban areas, have been accompanied by the generation of environmental problems as a result of population growth, population concentration, increased industrial activity, greater vehicular flow, increase in domestic activities and increased demand for the provision of services. Air pollution generated in a basin and its effects result in the need for constant monitoring, not only in the places where pollutants originate, but in adjacent areas.

The need of the community rests with local governments who must strive to obtain reliable information on the concentration of pollutants, their sources and their effects; It is imperative and fundamental for decision-making on the protection of people and ecosystems. The requirement for more reliable and quality information regarding air pollution levels is evident, which implies the need to implement and modernize monitoring systems in order to increase the representativeness, compatibility and validity of the information generated [1].

Air quality monitoring is of fundamental importance to identify and provide the necessary information to evaluate the air quality of each region and its trends, as a tool to develop prevention and control strategies, air quality management plans and comprehensive environmental policies, among other applications. Thus, in this context, Air Quality Monitoring Systems (SMCA) have become a tool that allows us to know, with acceptable levels of reliability, the air quality with respect to specific pollutants and formulate, based on the data obtained, control strategies and appropriate measures for effective environmental management. In general, among the objectives of air quality monitoring stand out; a) Evaluate compliance with the Official Mexican Standards (NOM) of environmental health, b) Assess the state of air quality with respect to the concentration of pollutants criterion, c) Quantify the levels of exposure of the population to air pollution, d) Provide immediate information for the activation or deactivation of environmental alerts, derived from a concentration of pollutants associated with human activities and/or natural sources, which may represent a risk, e) Inform the population in a timely manner about the state of air quality, f) Generate information for the evaluation of the spatial distribution and transport of air pollutants, g) Generate reliable data for the evaluation and monitoring of air quality management strategies [2]. Thus, with these objectives, it is intended that local governments make an integrated management of air pollution and implementing public policies in order to reduce the environmental and health risks.

During the first years of this decade, air pollution in the Monterrey Metropolitan Area (MMA) has generated a constant interest in citizens and authorities, due to poor air quality events, therefore, through the monitoring of meteorological parameters and criteria pollutants, emission sources can be evidenced, trends in the behavior of the parameters and create actions for the prevention, control and mitigation of air pollution.

Thus, the objective of this research is to show the evolution of air pollution in the first two decades of this century and evaluate the trend of the same and highlight the risks to which the inhabitants and urban ecosystems of this metropolis are subjected.

2. BACKGROUND

The Monterrey Metropolitan Area is one of the fastest growing areas in Mexico. As a result of this growth, this important urban and industrial center has begun to experience a degradation of air quality. The MMA is located in northeastern Mexico in an atmospheric basin bordered to the west by the Sierra Madre Oriental Mountain range (2500 masl) and to the south by low mountainous terrain (1200 masl). The MMA is surrounded by the Sierra Madre Oriental, the Cerro de la Silla, the Cerro de las Mitras and the Cerro del Topo Chico, which constitute a natural physical barrier for the circulation of the wind and prevent the evacuation of polluted air to the outside of the area [3]. The urban area sits on an inhomogeneous plain at an altitude of 540 m with lower altitudes in the east. The climate is classified as hot and dry with hot summers and cold winters and is affected by prevailing southerly winds and most days are under clear sky conditions. Rainfall is mainly concentrated in summer. The average annual temperature is 22.3°C. In August average temperatures of up to 28.4 °C is reached, while in January the average temperature is 14.6°C. The average annual rainfall is 583.2 mm [4].

The Monterrey Metropolitan Area of is the metropolitan area formed by the city of Monterrey, its homonymous municipality, and twelve other municipalities of the state of Nuevo León (Apodaca, Guadalupe, General Escobedo, Juárez, San Nicolás de los Garza, García, Santa Catarina, Pesquería, San Pedro Garza García, Cadereyta de Jiménez, Salinas Victoria and Santiago). Likewise, there is a region that forms a ring that surrounds the metropolitan area and that due to the high growth of the urban area of Monterrey (25 ha per week from 2000 to 2006) it is very likely that in the coming years they will be incorporated into the MMA: these municipalities are Abasolo, Ciénega de Flores, Doctor González, El Carmen, General Zuazua, Hidalgo, Higueras, Marín and Mina (Figure 1). According to the 2020 census [5] it is the second most populated metropolitan area in Mexico with 5,341,171 inhabitants, the second with the largest territorial extension, and the 81st metropolitan area in the world. It ranks second in economic generation, of which the manufacturing and services sectors contribute the main economic spillover. With respect to the vehicle fleet, there are more than two million motor vehicles in circulation, of which 73.4% correspond to cars for official, public and private use, followed by 23% of trucks and cargo vans. To a lesser extent are passenger trucks (0.8%) and motorcycles (2.6%) [4]. The MMA is characterized by its high industrial activity. PROAIRE 2008-2012 [3], mentions that the main industries in the region are steel, machinery manufacturing, metal articles, automotive, pulp and paper, glass, clay, earthenware, ceramics, textiles, cement, electrical, electronics, among others. Given a panorama of constant growth in the MMA, the monitoring of atmospheric pollutants is a fundamental part to establish the health effects that may arise in the population. For this, the Air Quality Monitoring System (SMCA) was established since 1992, which aims to measure the concentrations of atmospheric pollutants and monitor the level of exposure of citizens, issuing warnings when episodes of intense air pollution occur.

Fig. 1. Location of the Monterrey Metropolitan Area. Courtesy of Google Maps

Currently the SMCA of the MMA consists of 14 automatic monitoring stations. Three stations are located in the municipality of Monterrey, two in San Nicolás de los Garza and one more in each of the following municipalities: Apodaca, General Escobedo, García, Cadereyta, Juárez, Guadalupe, San Pedro Garza García, Santa Catarina and Pesquería. However, not all of them began operating in the same year; 5 began operations in 1992 (Obispado, San Bernabé, La Pastora, San Nicolás and Santa Catarina), two in 2009 (Escobedo and García), two more in 2012 (Apodaca and Juárez), one in 2014 (San Pedro), three more in 2017 (Pueblo Serena, Cadereyta and Universidad) and one in 2020 (Pesquería). In general, all stations are monitored automatically and have the capacity to measure suspended particles, both PM_{10} and $PM_{2.5}$ (Table 1 and Figure 2).

Table 1. SMCA stations in the Monterrey Metropolitan Area

Municipality	Population 2020	Station	Key	Equipment and start of operation	Pollutant					
					PM_{10}	$PM_{2.5}$	O_3	OS_2	NO_2	CO
Monterrey	1 239 812	Obispado	CE	Automatic (1992)	X	X	X	X	X	X
		San Bernabe	NO	Automatic (1992)	X	X	X	X		X
		Pueblo Serena	S	Automatic (2017)	X	X	X	X		X
Apodaca	657 912	Apodaca	NE2	Automatic (2012)	X	X			X	X
General Escobedo	440 045	Escobedo	N	Automatic (2009)	X	X				X
Garcia	213 744	Garcia	NO2	Automatic (2009)	X	X	X	X	X	X
Cadereyta	103 459	Cadereyta	SE3	Automatic (2017)	X	X	X	X	X	X
Juarez	379 742	Juarez	SE2	Automatic (2012)	X	X		X	X	X
Guadalupe	753 384	La Pastora	SE	Automatic (1992)	X	X	X	X		X
San Nicolas	466 913	San Nicolas	NE	Automatic (1992)	X	X	X	X	X	X
		Universidad	N2	Automatic (2017)	X	X	X	X	X	X
San Pedro	138 287	San Pedro	SO2	Automatic (2014)	X	X	X	X	X	X
Santa Catarina	304 148	Santa Catarina	SO	Automatic (1992)	X	X	X	X	X	X
Pesquería	31 420	Pesquería	NE3	Automatic (2020)	X		X	X	X	X

X= There is monitoring equipment for this pollutant. Source: Own elaboration with information provided by the Secretariat of Sustainable Development of Nuevo León.

Criteria contaminants

Air pollutants can be classified according to their source of origin in a) Natural Sources: which are generated due to processes that occur in nature and that in general terms can be characterized by low values of pollutant emissions (volcanic eruptions, natural forest fires, sea breeze, decomposition of organic matter, among others) and b) Anthropogenic sources: which are the result of human activities such as energy generation, food production, transfer and transformation of materials for human use (industrial chimneys, vehicle emissions, burning of waste materials, waste management, among others).

Of anthropogenic sources, emissions can come from (a) Mobile sources that are any pollutant-emitting device that does not have a fixed location; and (b) Fixed assets, which is any established facility that develops industrial, commercial, service or activity processes that generate emissions of pollutants into the atmosphere.

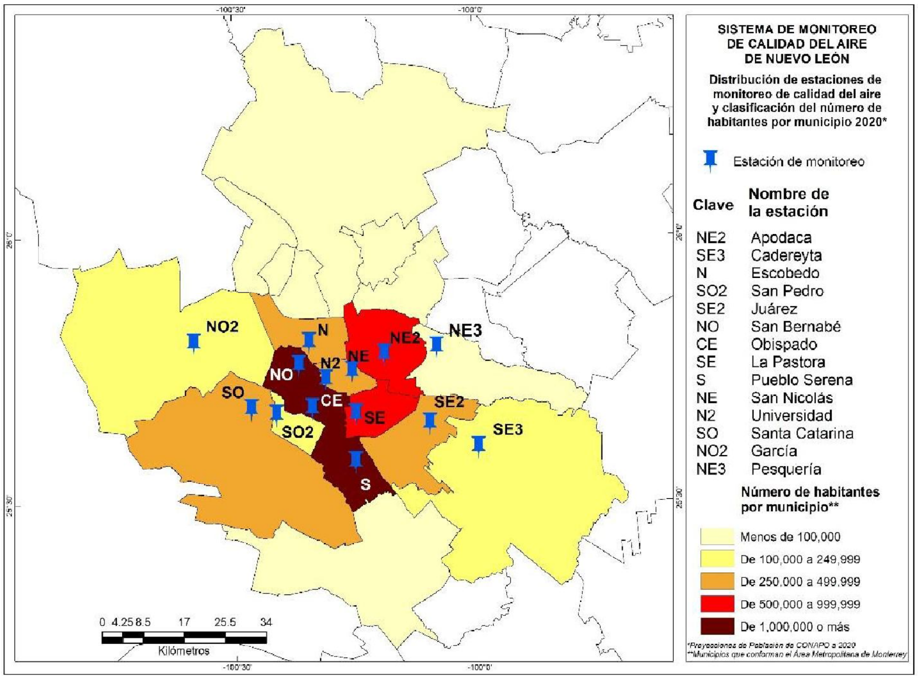

Fig. 2 SMCA map of the Monterrey Metropolitan Area in 2020.

Once pollutants are emitted into the atmosphere, they can interact and react with other chemical species present in the atmosphere, so they can be divided into: a) Primary pollutants that are those that are emitted directly into the atmosphere and that can interact with other chemical compounds or remain unchanged in the atmosphere; and b) Secondary pollutants resulting from chemical reactions in the atmosphere, either between gases in the air and primary pollutants, water vapor and in the presence of solar radiation.

It has been proven that there is a relationship between air pollutants and negative health effects of both humans and ecosystem elements. The World Health Organization (2014) [6] showed that 90% of people living in places where there is poor air quality recorded approximately 3 million premature deaths. This is due to exposure in short periods of time and high concentrations of pollutants, which triggers respiratory and cardiovascular diseases. Likewise, the United States Environmental Protection Agency (USEPA) [7] considers as Criteria Pollutants a group of six pollutants that are the most common that are present in the atmosphere worldwide. Of the criteria pollutants, the conditions or maximum permissible limits to which the population can be exposed in periods of 24 hours have been established. Table 2 describes the maximum permissible limits for Mexico according to the Official's Norms in Environmental Health.

Health effects of criteria pollutants

Exposure to criteria contaminants may be related to possible effects on human health. Air pollutants, depending on their concentrations and exposure times, can influence the presence and exacerbation of diseases in vulnerable populations such as minors, older adults and people with respiratory and cardiovascular diseases. Table 3 shows the main health effects of both short- and long-term contaminants.

Air pollution in the MMA

The MMA has been characterized by its high industrial and service activity, so that the sustained development of the metropolis has complicated to order the industrial sectors that coexist with the urban settlements distributed throughout its almost 6357 km^2. On the other hand, the horizontal housing development of the MMA is a great challenge for the mobility of its inhabitants, so unfortunately there has been an increase in private motor vehicles, as well as public and cargo transport, which increases emissions of criteria pollutants. On the other hand, the entrenched use of burning wood and charcoal as part of the daily life of the inhabitants of the MMA complicates and increases the emissions of criteria pollutants.

On the other hand, the activities of the MMA, its geographical characteristics such as mountain systems, meteorological and climatological phenomena typical of the area, contribute to the concentration of pollutants emitted into the atmosphere and their dispersion in the heights and to other regions to reduce their concentration in the MMA. Air pollution has led to the MMA now being considered a metropolis with "Poor Air Quality Levels". The number of days outside the norm has been gradually increasing, putting at risk the quality of life of its inhabitants. Figure 2 shows in a general way how the maximum permissible limits have been exceeded during a large number of days between 2016 and 2019. Figures 3 and 4 shows by air pollutant the days out of the norm in 2019 in the MMA.

Table 2 Criteria pollutants and maximum permissible limits

Criterion Pollutant	Description	Exposure limit	Exposure time
Particulate matter smaller than 10 µm (PM_{10})[a]	Complex mixture of solid and liquid particles smaller than 10 micrometers in size	70 kg/m^3	24 h
		36 kg/m^3	1 year
Particulate matter smaller than 2.5 µm ($PM_{2.5}$)[a]	Complex mixture of solid and liquid particles smaller than 2.5 micrometers in size	41 kg/m^3	24 h
		10 kg/m^3	1 year
Ozone (O_3)[b]	Secondary gas composed of 3 O atoms, formed by some primary pollutants in the presence of solar UV radiation	0.090 ppm	1 h
		0.065 ppm	8 am
Carbon monoxide (CO)[c]	Gas produced mainly by combustion, which in high concentrations is harmful to health	26 ppm	1 h
		9 ppm	8 am
Sulphur dioxide (SO_2)[d]	Gas composed of two atoms of oxygen and one of sulfur, product of the combustion of fossil fuels with high sulfur content.	0.075 ppm	1 h
		0.04 ppm	24 h
Nitrogen dioxide (NO_2)[e]	Gas composed of two atoms of oxygen and one of nitrogen, product of combustion at more than 1000 ° C.	0.106 ppm	1 h
		0.021 ppm	1 year

[a]Official Mexican Standard NOM-025-SSA1-2021, Environmental health. Criterion for assessing ambient air quality, with respect to PM_{10} and $PM_{2.5}$ suspended particles. Normed values for the concentration of suspended particles PM $_{10}$ and $PM_{2.5}$ in ambient air, as a measure to protect the health of the population [8].
[b]Official Mexican Standard NOM-020-SSA1-2021, Environmental health. Criterion for assessing ambient air quality, with respect to ozone (O_3). Normed values for the concentration of ozone (O_3) in ambient air, as a measure to protect the health of the population [9].
[c] Official Mexican Standard NOM-021-SSA1-2021, Environmental Health. Criteria for assessing ambient air quality, with respect to carbon monoxide (CO). Normed values for the concentration of carbon monoxide (CO) in ambient air, as a measure to protect the health of the population [10].
[d]Official Mexican Standard NOM-022-SSA1-2019, Environmental health. Criterion for assessing ambient air quality, with respect to sulphur dioxide (SO2). Normed values for the concentration of sulfur dioxide (SO2) in ambient air, as a measure to protect the health of the population [11].
[e] Official Mexican Standard NOM-023-SSA1-2021, Environmental Health. Criterion for assessing ambient air quality, with respect to nitrogen dioxide (NO2). Normed values for the concentration of nitrogen dioxide (NO^2) in ambient air, as a measure to protect the health of the population [12].

Based on the data described above, it is important to evaluate the evolution of air pollutants during the last two decades, since this will allow to evidence the possible causes, origins and destination of pollutants and through the development of adequate public policies to prevent concentrations of pollutants from continuing to increase and avoid affecting the population and ecosystems.

Table 3 Main health effects of criteria pollutants

Criterion pollutant	Short-term effect	Long-term effect
Particulate matter PM_{10} and $PM_{2.5}$	Increased respiratory morbidity and mortality Decreased Lung Function Interference with pulmonary defense mechanisms Obstructive bronchial syndrome	Decreased development of the structure and function of the respiratory system Increased risk of cancer in adulthood (PAHs)
Ozone (O_3)	Decreased breathing rate Neutrophilic alveolitis, increased permeability and bronchial hyperactivity Alteration of the alveolar epithelium	Epithelial cell damage, alveolar "bronchization" Decreased development of FVC and FEV
Carbon monoxide (CO)	Decreased exercise capacity	
Sulphur dioxide (SO_2)	Bronchial obstruction Bronchial hypersecretion	Chronic bronchitis
Nitrogen dioxide (NO_2)	Bronchial hyperreactivity Increased respiratory symptoms and asthma exacerbations Increased response to provocation with allergens Decreased mucociliary activity	Possible decrease in lung development

Thus, the objective of this research is to show the evolution of air pollution in the first two decades of this century and evaluate its trend and highlight the risks to which the inhabitants and urban ecosystems of this metropolis are subjected.

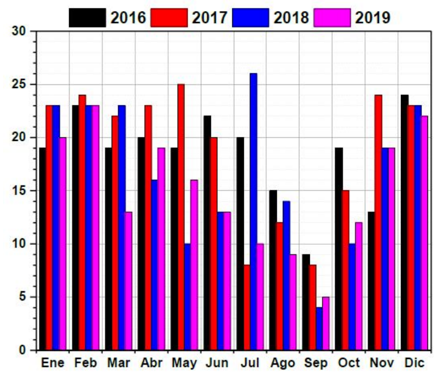

Figure 3. Days out of Environmental Health NOMs in the MMA (2016-2019)

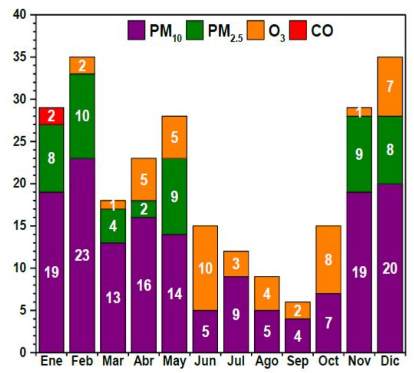

Figure 4. Days out of Environmental Health NOMs by pollutant in the MMA in 2019

3. MATERIALS AND METHOD

The air quality data to evaluate the evolution of air pollution in the MMA were taken from the databases of the Environmental Monitoring Integral System (SIMA) [13] of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León, and the National Air Quality Information System (SINAICA) [14] of the National Institute of Ecology and Climate Change (INECC) belonging to the Ministry of Environment and Natural Resources(SEMARNAT) of the Government of Mexico. As already mentioned, the SIMA of the MMA has 14 monitoring stations of criteria pollutants distributed in the MMA. Concentrations of CO, NO_2, SO_2, PM_{10}, $PM_{2.5}$ and O_3 were evaluated. The trend of the hourly, daily, monthly and annual time series was evaluated to see how air pollution patterns and the distribution of pollutants in the MMA have changed.

The data used were validated through the SINAICA data validation protocol so that the values did not cause bias in the trends. From the original databases subsets were calculated: (a) hourly averages, b) averages every 8 h, c) daily averages, d) monthly averages and e) annual averages of the 14 stations during the period 2000-2020 for the six criteria pollutants. It is important to clarify that we worked with the existing data, since it must be considered that not all stations have their complete data series, due to multiple factors such as: that some stations do not have some of the sensors for certain pollutants, on other occasions some sensors stopped operating, some stations underwent maintenance or renovation, among other obstacles to not being able to have the complete 2000-2020 time series.

From the five subsets of data, several calculations were made in order to observe the trends and distribution of pollutants throughout the MMA. The spatial and temporal behavior of the concentrations of criterion pollutants was And the spatial distribution was made by the method of graphical interpolation of kriging to estimate the trend and distribution of each of the criterion pollutants during the period 2000-2020.

4. RESULTS AND DISCUSSION

The results will be described by pollutant, analyzing the time series, hourly, daily, monthly and annual. Likewise, the spatio-temporal distributions of the years 2000, 2005, 2010, 2014 and 2020 were analyzed and compared with previous studies.

PM_{10}

Particles smaller than 10 microns show for hourly average analysis, that most data are above NOM-025-SSAI-2021 [8] for both 24 hours (70 µg/m^3) and annual (36 µg/m^3). As for the daily time series (Figure 5) the behavior is equal to those of the hourly averages. In both cases the trend over time is one of increase from the year 2000 to 2020. However, analyzing the values of monthly averages (Figure 5) shows a contrary behavior where there is a tendency to decrease monthly averages as the century advances, however all above the NOM-025-SSAI-2021. Regarding the spatial distribution, the maps allow us to observe that the concentrations can vary from one month to another and from one year to another, taking the maximum average values of each year it is evident that the years 2005 and 2014 presented values well above the norm mainly west of the MMA. The years 2000, 2010 and 2020 present a more homogeneous distribution above the annual and daily norm (Figure 6). The days outside the norm in the period 2000-2020 is approximately 165 days (45% of the year).The inventory of emissions of pollutants criterion, reports that the particulate matter or emitted was 157,761 tons, 40% corresponds to PM_{10}, which in this type of source, are included industrial and commercial establishments of various lines, as well as service and domestic activities whose emissions are estimated collectively [3]. On the other hand, in a study carried out for the period between 2000-2011, the annual averages for PM_{10} are above 40 µg/m^3 [15], which coincides with the results evidenced in the analysis between 2000-2020.

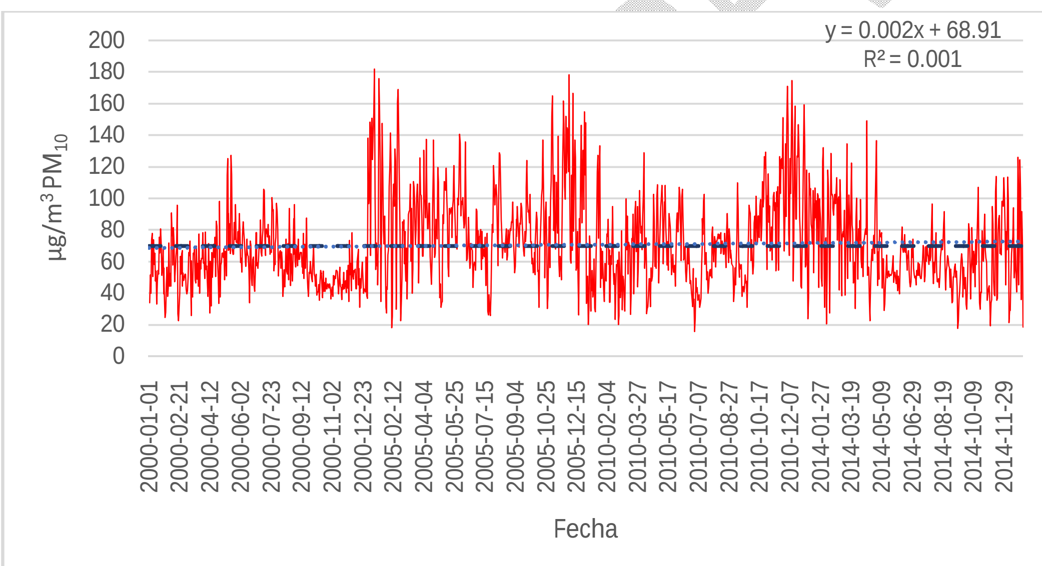

Fig. 5 Daily average of PM_{10} in µg/m^3 in the MMA (2000, 2005, 2010 and 2014)

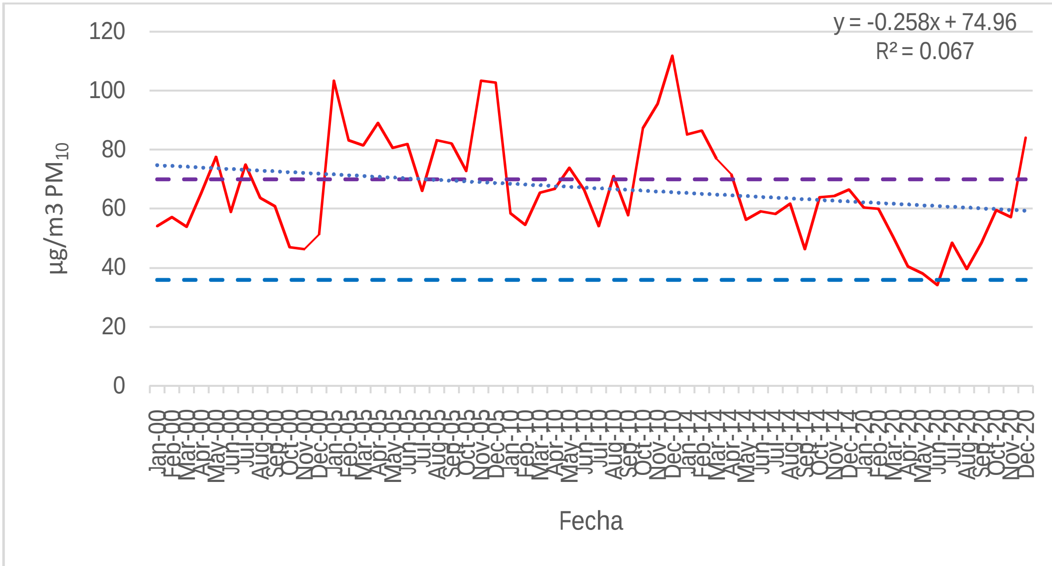

Fig. 6 Monthly average of PM_{10} in µg/m^3 in the MMA (2000, 2005, 2010, 2014 and 2020).

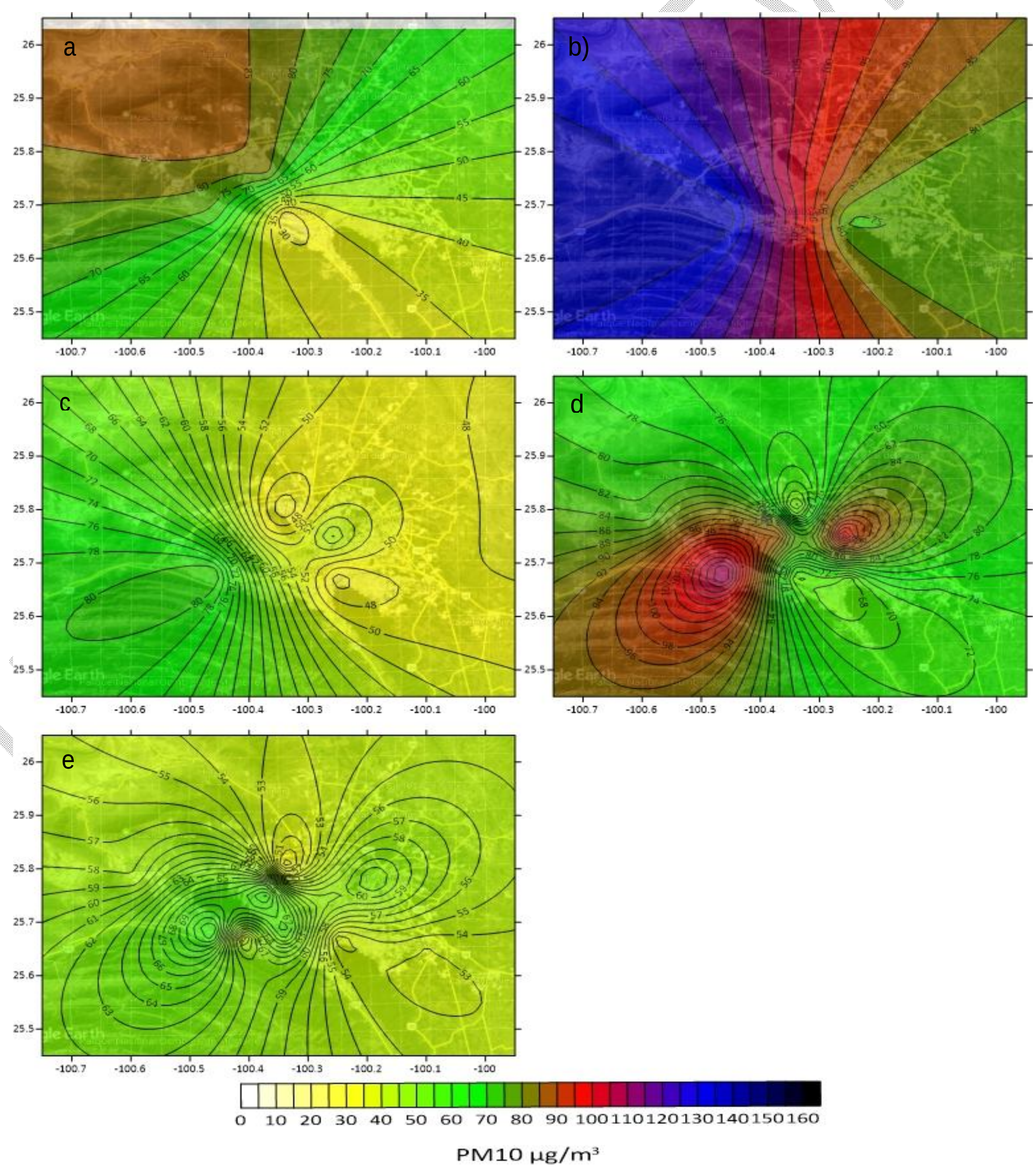

Fig. 7 Temporal space distribution for the highest month of PM_{10} (µg/m^3) in the MMZ; a) 2000, b) 2005, c) 2010, d) 2014 and e) 2020).

$PM_{2.5}$

For particles smaller than 2.5 microns the hourly average analysis shows that most data are below the NOM-025-SSAI-2021 [8] for 24 hours (41 µg/m^3), but above the annual (10 µg/m^3), few events occur above the 24 h norm. As for the daily time series (Figure 8) the behavior is equal to those of the hourly averages. In both cases the trend over time is a decrease in hourly and daily averages from 2000 to 2020. Analyzing the values of monthly averages (Figure 9) shows a downward trend in monthly averages as the century progresses, however all above the NOM-025-SSAI-2021. The spatial distribution shows like the PM_{10} that concentrations can vary from month to month and from year to year, taking the maximum average values of each year it is evident that the years 2000 and 2010 presented values well above the norm practically throughout the MMA. The years 2005, 2014 and 2020 present a more homogeneous distribution above the annual and daily norm (Figure 10). The days outside the norm in the period 2000-2020 is approximately 36 days (10% of the year).

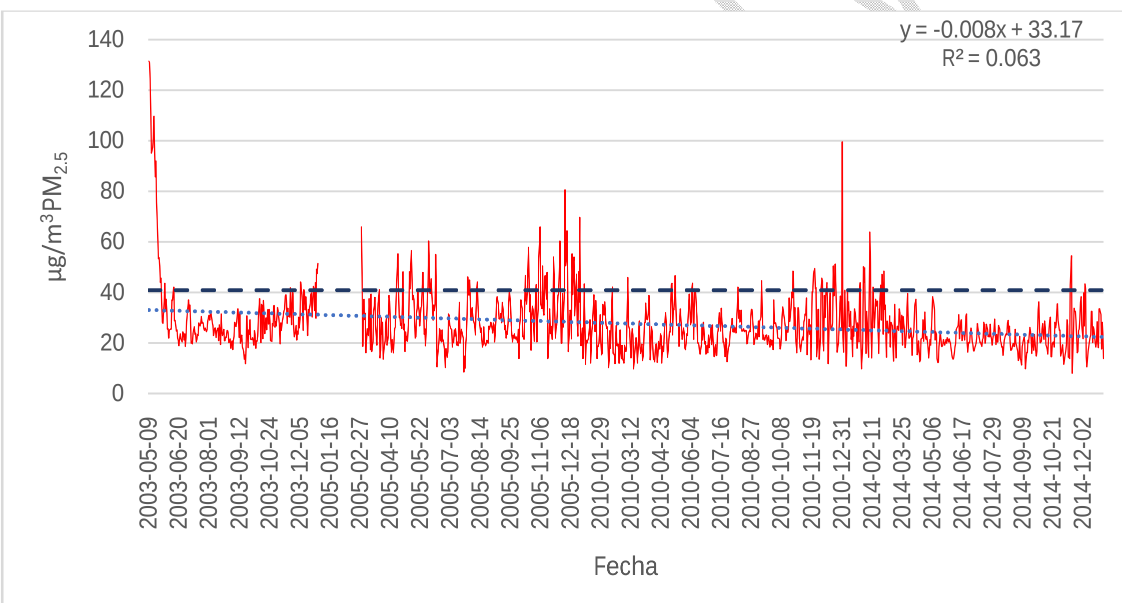

Fig. 8 Daily average of $PM_{2.5}$ in µg/m^3 in the MMA (2000, 2005, 2010 and 2014)

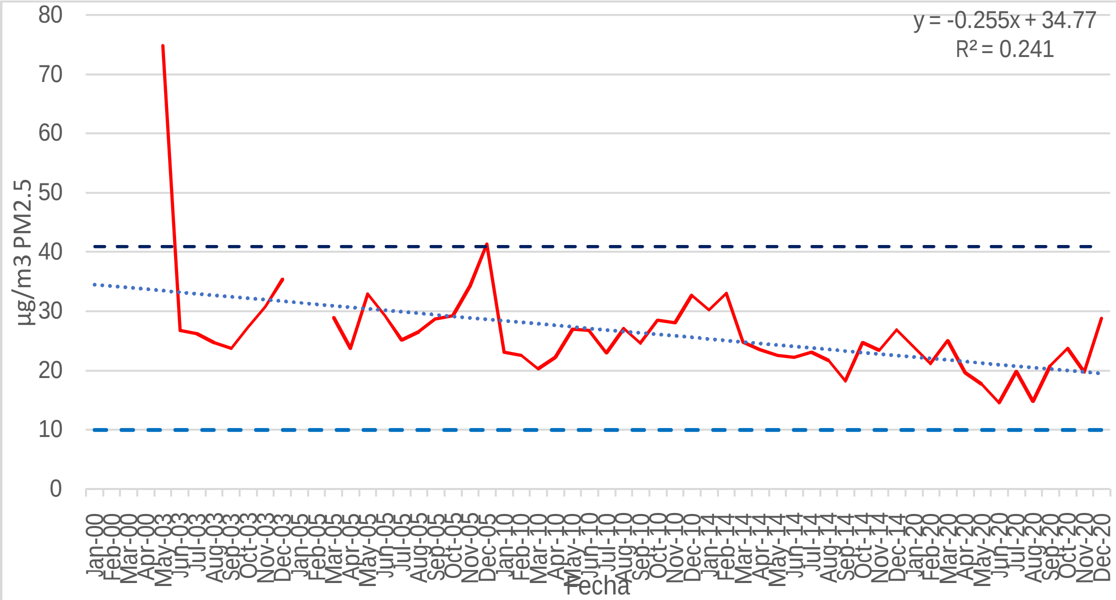

Fig. 9 Monthly average of $PM_{2.5}$ in $\mu g/m^3$ in the MMA (2000, 2005, 2010, 2014 and 2020)

O_3

Analysis of hourly average ozone concentrations shows that most data are below NOM-020-SSAI-2021 [9] for 1 hour (0.090 ppm), as well as for 8 h (0.060 ppm), there are some hourly events that are above the limits permissible by the standard. As for the daily time series (Figure 11) the behavior is equal to those of the hourly averages. In both cases the trend over time is a marked increase in hourly and daily averages from 2000 to 2020. Analyzing the values of monthly averages (Figure 12) shows a trend of increase in monthly averages as the century progresses, however all below the NOM-020-SSAI-2021. The spatial distribution shows as well as the concentrations of O_3 can vary from one month to another and from one year to another, taking the maximum average values of each year it is evident that the years 2000, 2010, 2014 and 2020 presented the highest values, although below the norm mainly to the west and south of the MMA. The year 2005 presents a more homogeneous distribution with values well below the annual and daily norm (Figure 13). The days outside the norm in the period 2000-2020 is approximately 63 days (17% of the year). The reports of days out of the norm for O_3, were in 2017, 40 days; in 2018, 10 days; in 2019 48 days and 2020, 32 days; below the average between 2000-2020 of 63 days outside the norm [18-21].

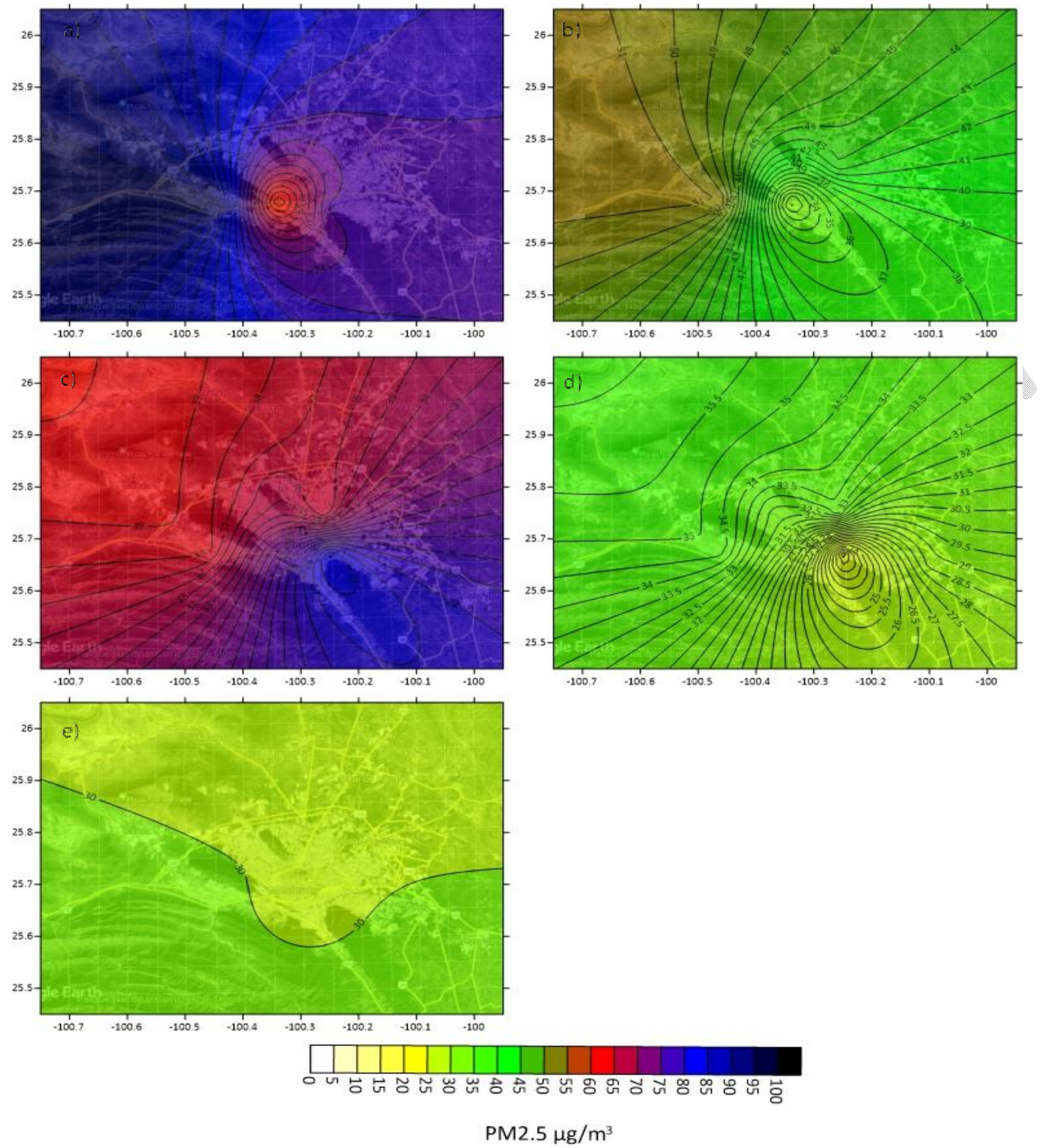

Fig. 10 Temporal space distribution for the highest month of $PM_{2.5}$ ($\mu g/m^3$) in the MMA; a) 2000, b) 2005, c) 2010, d) 2014 and e) 2020).

SO_2

Analysis of hourly average concentrations of sulfur dioxide shows that most data are well below NOM-022-SSAI-2019 [11] for 1 hour (0.0 75 ppm), as for 24 h (0.040 ppm). As for the daily time series (Figure 14) the behavior is equal to those of the hourly averages. In both cases the trend over time is a decrease in hourly and daily averages from 2000 to 2020. Analyzing the values of monthly averages (Figure 15) shows a trend of decrease in monthly averages as the century progresses. The spatial distribution shows that the concentrations of SO_2 can vary from month to month and from year to year, taking the maximum average values of each year it is evident that all years presented a very homogeneous distribution with values well below the annual and daily norm (Figure 16) except for the year 2000 that presented the highest values north of the MMA. There were no days out of the norm throughout the period analyzed. The 2017, 2018, 2019 and 2020 reports do not report days out of the norm for SO_2, so it does not represent a risk [18-21].

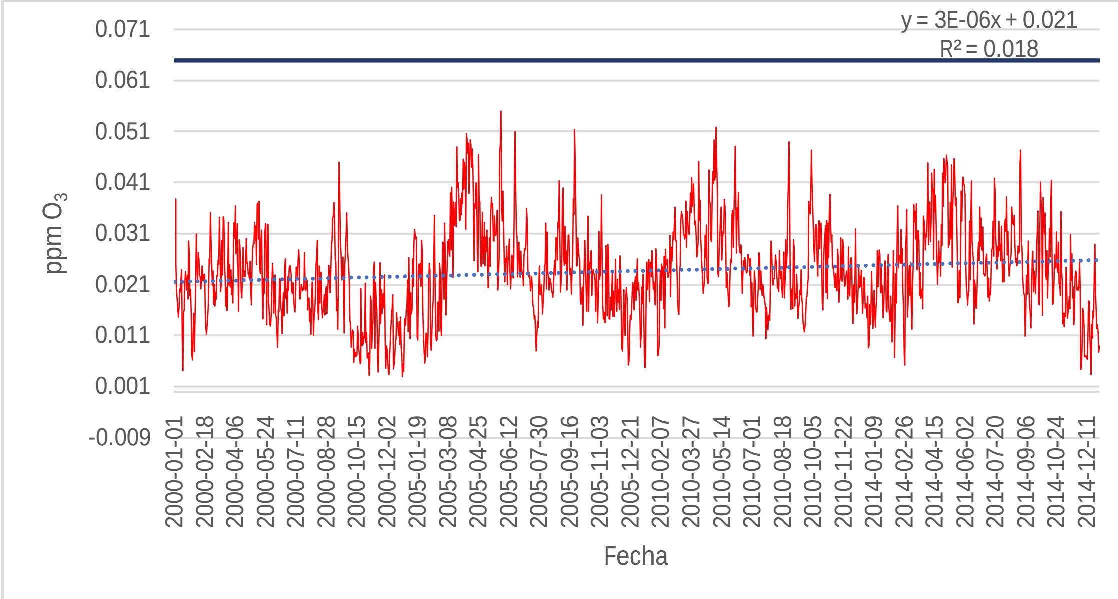

Fig. 11 Daily average of O_3 in ppm in the MMA (2000, 2005, 2010 and 2014)

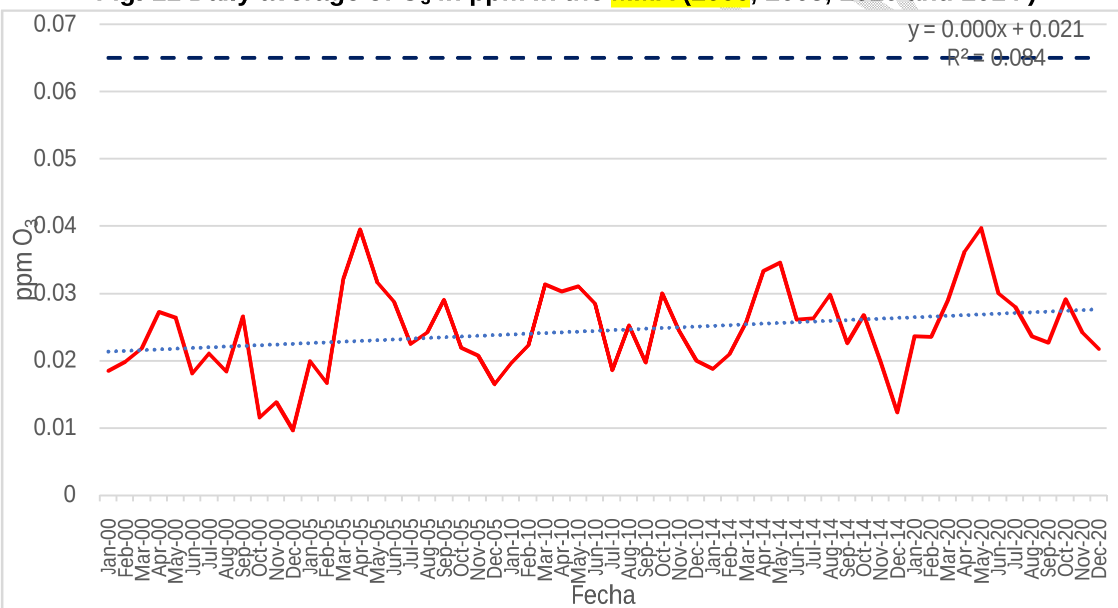

Fig. 12 Monthly average of O_3 in ppm in the MMA (2000, 2005, 2010, 2014 and 2020)

NO_2

Analysis of hourly average concentrations of nitrogen dioxide shows that most data are well below NOM-023-SSAI-2019 [12] for 1 hour (0. 106 ppm), but many events with values above the annual norm (0.021 ppm). As for the daily time series (Figure 17) the behavior is equal to those of the hourly averages. In both cases the trend over time is a slight decrease in hourly and daily averages from 2000 to 2020. Analyzing the values of monthly averages (Figure 18) shows a trend of decrease in monthly averages as the century progresses. The spatial distribution shows that the concentrations of NO_2 can vary from month to month and from year to year, taking the maximum average values of each year it is evident that the years 2000, 2010 and 2014 presented the highest concentrations above the annual norm the eastern and southern part of the MMA, while the year 2005 shows a more homogeneous distribution with values above the annual norm (Figure 19). There were no days out of the daily norm. The 2017, 2018, 2019 and 2020 reports do not report days out of the norm for NO_2, so it does not represent a risk [18-21].

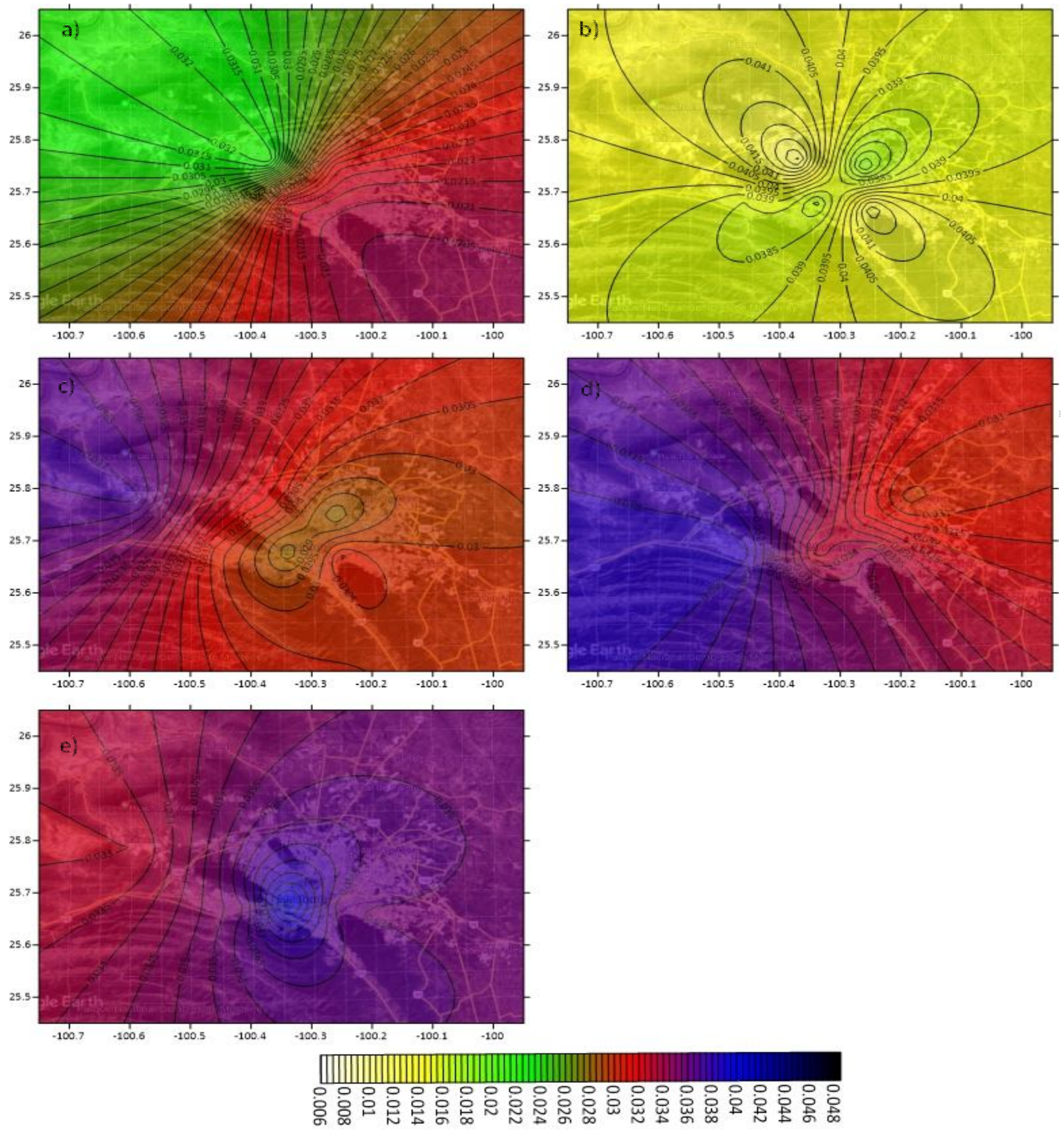

Fig.13 Temporal space distribution for the highest month of O_3 (ppm) in the MMA a) 2000, b) 2005, c) 2010, d) 2014 and e) 2020).

CO

Analysis of hourly average concentrations of carbon monoxide shows that most data are well below NOM-021-SSAI-2021 [10] for 1 hour (26 ppm), and for 8 hours (9 ppm), so they currently pose no risk. As for the daily (Figure 20) and monthly (Figure 21) time series, the behavior is the same as those of the hourly averages. Thus, the trend over time is a slight decrease in hourly, daily and monthly averages from 2000 to 2020. The spatial distribution shows that the concentrations of CO can vary from one month to another and from one year to another, taking the maximum average values of each year it is evident that the years 2000 and 2005 presented a homogeneous distribution with very low values with respect to the norm, while 2010 and 2014 presented higher concentrations but still low compared to the norm (Figure 22). There were no days out of the daily norm. The reports of 2017, 2018 and 2019 do not report days out of norm; the year 2020 presented 2 days out of norm [18-21].

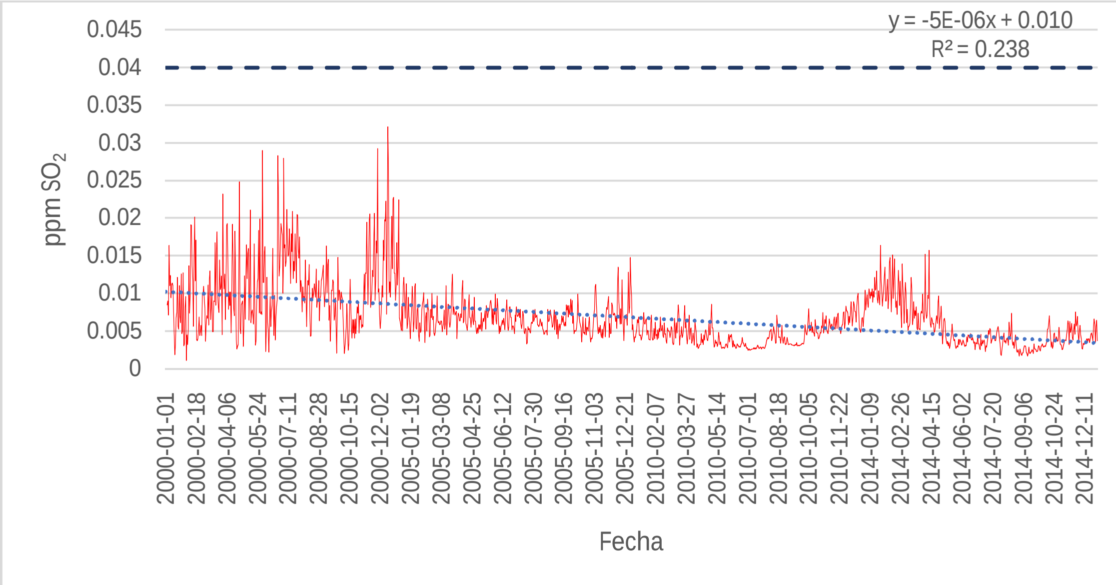

Fig. 14 Daily average of SO_2 in ppm in the MMA (2000, 2005, 2010 and 2014)

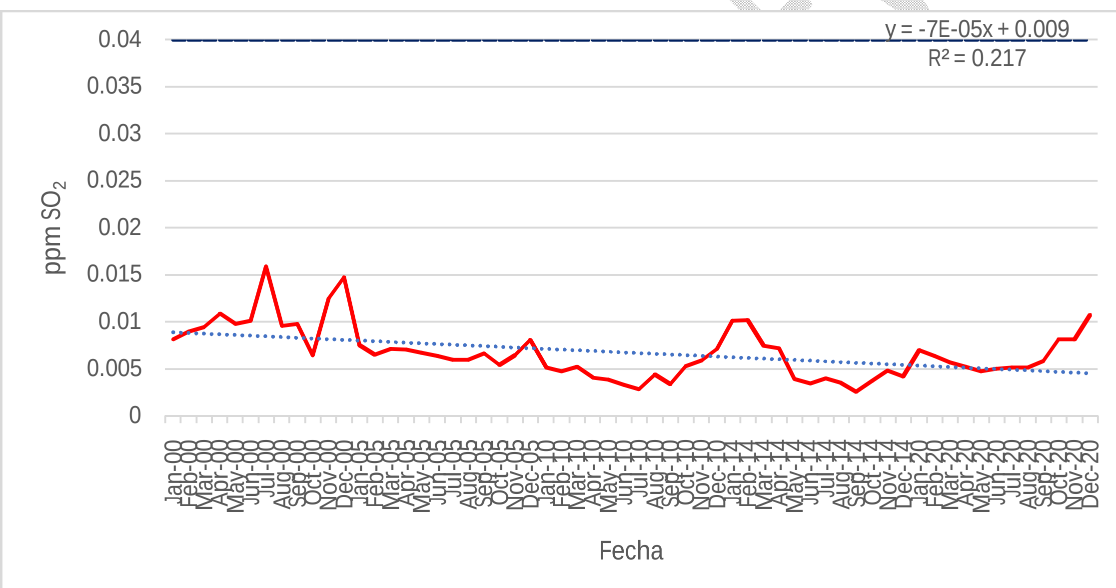

Fig. 15 Monthly average of SO_2 in ppm in the MMA (2000, 2005, 2010, 2014 and 2020)

In general, the results show that pollutants have a great variability and these depend on multiple natural factors (thermal inversion, wind speed and direction, orography, among others) and/or anthropogenic factors (mobility, agricultural, industrial, service, fire, among others). They also depend on the time of year, presenting an increase in particulate matter in the dry months and ozone in the wet season.

According to the information available by the SMCA of the MMA for the year 2018 [18-19], the pollutant that most often determines a poor air quality condition is PM_{10}, followed by O_3 and $PM_{2.5}$. The daily (24-hour average) limit of PM_{10} was exceeded on 53% of days in 2018, while the regulated limit of $PM_{2.5}$ (24-hour average) and ozone (1-hour average) was exceeded by 10% of days. These results coincide with those reported here for the period 2000-2020, with a trend of increase of these 3 criteria pollutants, which coincides with the 45% data for PM_{10}, 10% for $PM_{2.5}$ and 17% for O_3 in the period 2000-2020 analyzed in the present study.

On the other hand, in the 2018 report, carbon monoxide, nitrogen dioxide and sulfur dioxide did not represent an air quality problem as they did not register days with concentrations above the corresponding normative limit [17]. Similarly, in the present study, CO, SO_2 and NO_2 do not represent any risk since their concentrations are well below the standards for these criteria pollutants.

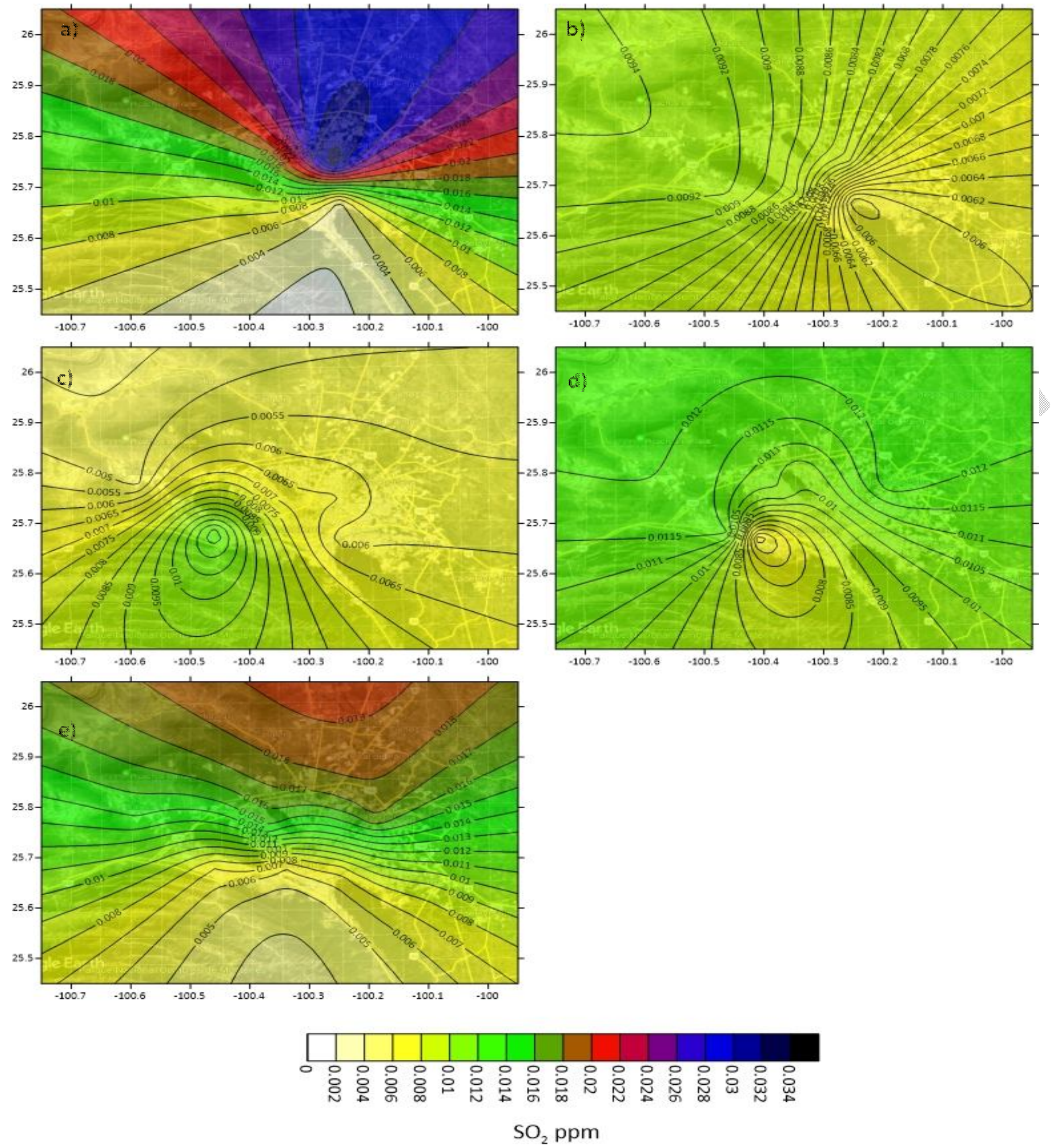

Fig. 16 Temporal space distribution for the highest month of SO_2 (ppm) in the MMA; a) 2000, b) 2005, c) 2010, d) 2014 and e) 2020).

CONCLUSIONS

The criteria pollutants that presented the highest number of days outside the norm and with the greatest tendency to increase during the last two decades are PM_{10}, $PM_{2.5}$ and O_3, which represents a risk to environmental and human health. The pollutants CO, NO_2, SO_2, so far do not represent a risk since these are within the norm both for the number of days and for the daily, annual and monthly averages.

Regarding the seasonal variation in the MMA, it was found that the highest concentrations of almost all pollutants occur in the cold months, probably due to the presence of thermal inversions that prevent the dispersion of pollutants; while the lowest levels are recorded during the rainy season due to the retention and dragging in raindrops. However, the secondary pollutant ozone does not present a clear pattern of behavior, since it depends on the number of primary pollutants and the presence of sunlight that lasts longer during the spring-summer months.

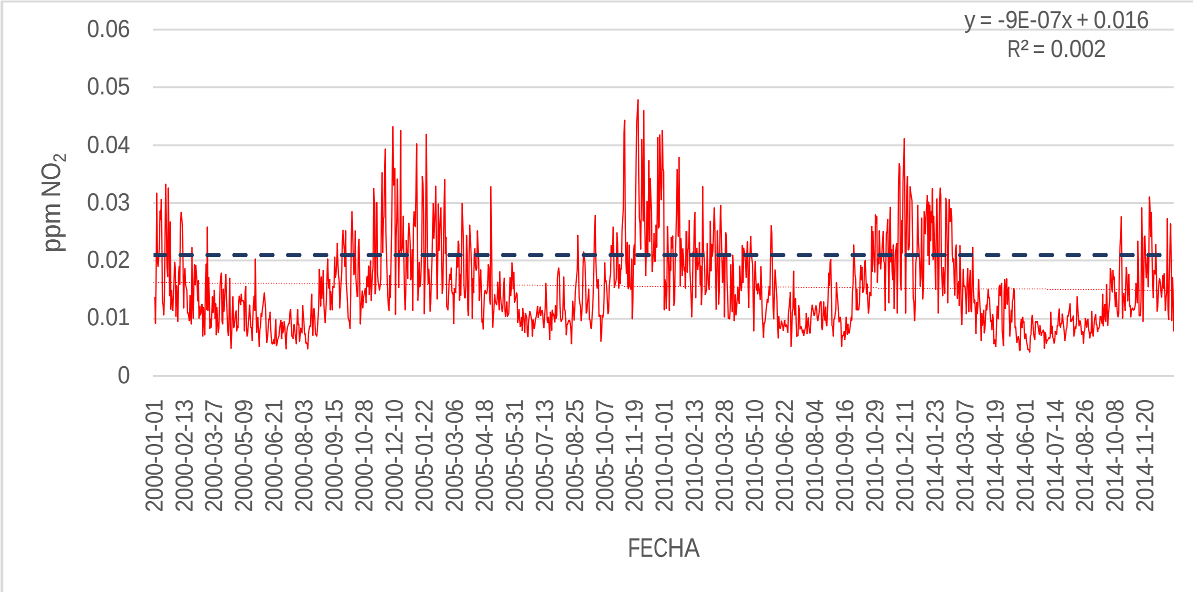

Fig. 17 Daily average of NO_2 in ppm in the MMA (2000, 2005, 2010 and 2014)

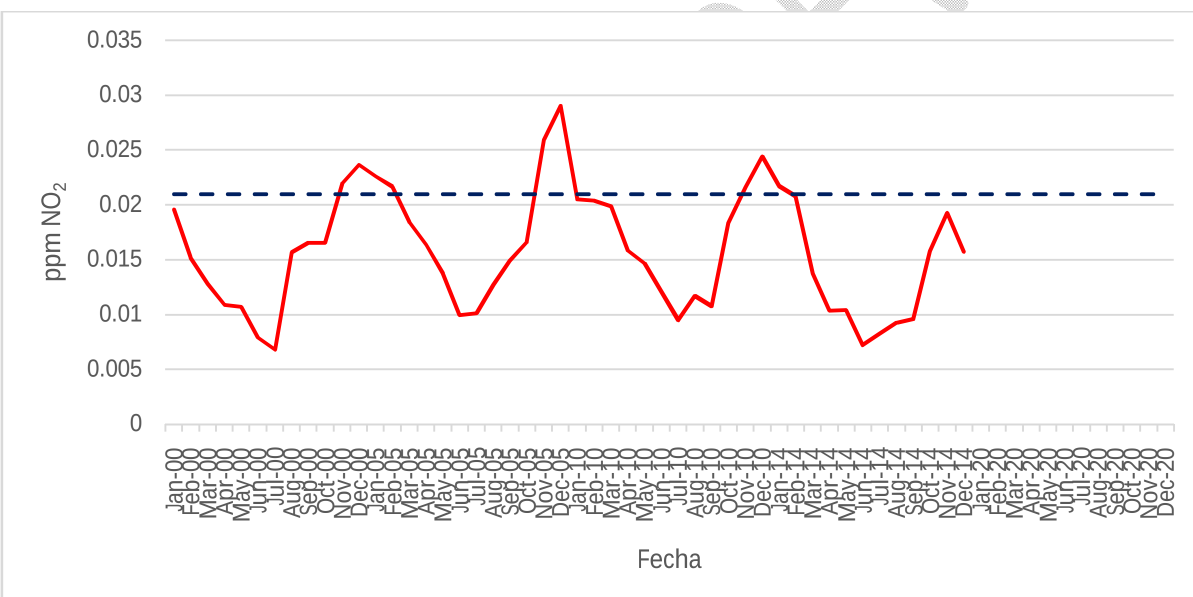

Fig. 18 Monthly average of NO_2 in ppm in the MMA (2000, 2005, 2010 and 2014)

REFERENCES

1. SEMARNAT 2012. Official Mexican Standard NOM-156-SEMARNAT-2012, Establishment and operation of air quality monitoring systems. Official Gazette of the Federation of July 16, 2012. Available for consultation at: dof.gob.mx/nota_detalle.php?codigo=52594648&fecha= 16/07/2012
2. Martinez, A.P., 1. Romieu. 1997. Introduction to atmospheric monitoring. ECO/GTZ/Department of the Federal District. Mexico. 238 pp.
3. PROAIRE, 2008-2012. Management Program to Improve Air Quality in the Metropolitan Area of Monterrey 2008-2012.
4. INEGI, 2014. National Institute of Statistics and Geography. Statistical and Geographic Yearbook of Nuevo León 2014.
5. INEGI, 2021. Population and Housing Census (2020). Population and Housing Census 2020 : Mconceptual arc/National Institute of Statistics and Geography.-- Mexico : INEGI, c2021.

6. WHO, 2014. World Health Organization. Air quality and health. Facts and Figures. Retrieved from: https://www.who.int/es/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-andhealth#:~:text= Se% 20estima%20que%20la%20contaminaci%C3%B3n,o%20menos%20de%20di%C3%A1metro% 20(PM2. 5)
7. USEPA National Ambient Air Quality Standards (NAAQS). https://www.epa.gov/criteria-air-pollutants
8. NOM-025-SSA1-2019 Official Mexican Standard NOM-025-SSA1-2021, Environmental Health. Criterion for assessing ambient air quality, with respect to PM_{10} and $PM_{2.5}$ suspended particles. Normed values for the concentration of suspended particles PM $_{10}$ and $PM_{2.5}$ in ambient air, as a measure to protect the health of the population. OFFICIAL JOURNAL Wednesday 27 October 2021. https://www.dof.gob.mx/nota_detalle.ph ?codigo=5633855&fecha=27/10/2021#gsc.tab=0
9. NOM-020-SSA1-2019 Official Mexican Standard NOM-020-SSA1-2021, Environmental Health. Criterion for assessing ambient air quality, with respect to ozone (O3). Normed values for the concentration of ozone (O3) in ambient air, as a measure to protect the health of the population. OFFICIAL JOURNAL Thursday 28 October 2021. https://dof.gob.mx/nota_detalle.php?codigo= 5633956&fecha=28/10/2021#gsc.tab=0
10. NOM-021-SSA1-2019 Official Mexican Standard NOM-021-SSA1-2021, Environmental health. Criteria for assessing ambient air quality, with respect to carbon monoxide (CO). Normed values for the concentration of carbon monoxide (CO) in ambient air, as a measure to protect the health of the population. OFFICIAL JOURNAL Friday, December 29, 2021. https://dof.gob.mx/nota_detalle.php?codigo=5634084&fecha=29/ 10/ 2021#gsc.tab=0
11. NOM-022-SSA1-2019 Official Mexican Standard NOM-022-SSA1-2019, Environmental health. Criterion for assessing ambient air quality, with respect to sulphur dioxide (SO2). Normed values for the concentration of sulphur dioxide (SO2) in ambient air, as a measure to protect the health of the population. OFFICIAL JOURNAL Tuesday 20 August 2019. https://dof.gob.mx/nota_detalle.php?codigo=5568395&fecha=20/08/ 20 19#gsc.tab=0
12. NOM-023-SSA1-2019 Official Mexican Standard NOM-023-SSA1-2021, Environmental health. Criterion for assessing ambient air quality, with respect to nitrogen dioxide (NO2). Normed values for the concentration of nitrogen dioxide (NO2) in ambient air, as a measure to protect the health of the population. OFFICIAL JOURNAL Wednesday 27 October 2021. https://www.dof.gob.mx/nota_detalle.php?codigo=5633854&fecha =27/10/2021#gsc.tab=0
13. SIMA. 2023, Integral Environmental Monitoring System (SIMA) of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León. http://aire.nl.gob.mx/index.html.
14. SINAICA, 2023. National Air Quality Information System (SINAICA) of the National Institute of Ecology and Climate Change (INECC) belonging to the Ministry of Environment and Natural Resources (SEMARNAT). https://sinaica.inecc.gob.mx/
15. Benítez-García, S., Isao Kanda, Shinji Wakamatsu, Yukiyo Okazaki and Masahide Kawano. 2014. Analysis of Criteria Air Pollutant Trends in Three Mexican Metropolitan Areas. Atmosphere 5: 806-829.
16. Martínez, M. A., Caballero, P., Carrillo, O., Mendoza, A. and Mejía, G.M. 2012. Chemical characterization and factor analysis of PM2.5 in two sites of Monterrey, Mexico. Journal of the Air & Waste Management Association 62: 817-827.
17. INECC, 2019. National Institute of Ecology and Climate Change - INECC, 2019. National Air Quality Report 2018, Mexico. Available for consultation at: https:sinaica.inecc.gob.mx/archivo/informes/ informe2018.pdf
18. SIMA, 2019. Air quality report for the year 2018 of the metropolitan area of Monterrey . Integral Environmental Monitoring System (SIMA) of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León.
19. SIMA, 2019. Report of meteorology and air quality of the metropolitan area of Monterrey December 2019. Integral System of Environmental Monitoring (SIMA) of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León.

20. SIMA, 2020. Air quality report for the year 2019 of the metropolitan area of Monterrey. Integral Environmental Monitoring System (SIMA) of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León.

21. SIMA, 2021 Annual report on the trend of air quality in the Monterrey Metropolitana 2020. Integral Environmental Monitoring System (SIMA) of the Directorate of Integral Management of Air Quality of the Ministry of Environment of the Government of the State of Nuevo León.

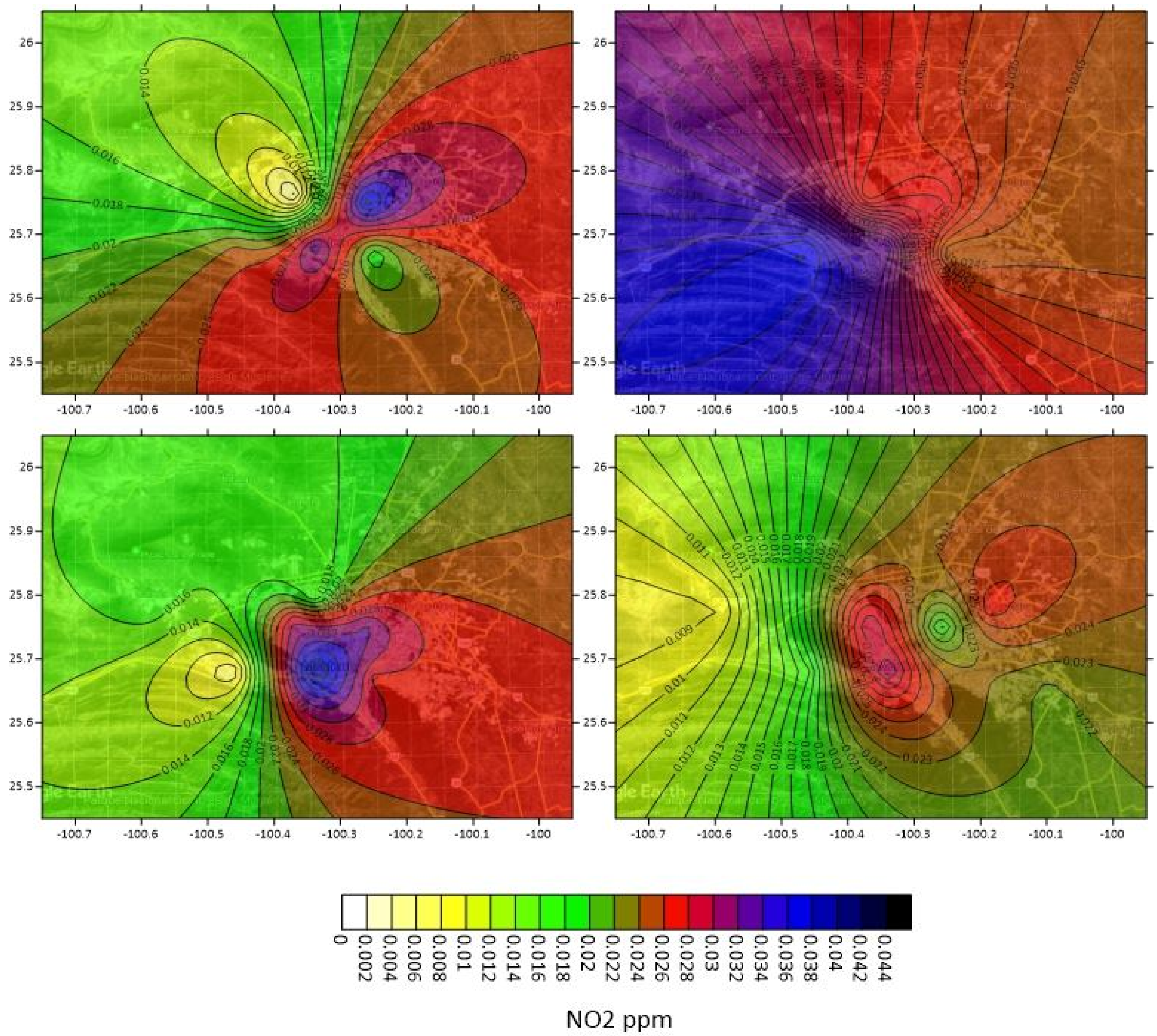

Fig. 19 Temporal space distribution for the highest month of NO_2 (ppm) in the MMA; a) 2000, b) 2005, c) 2010 and d) 2014.

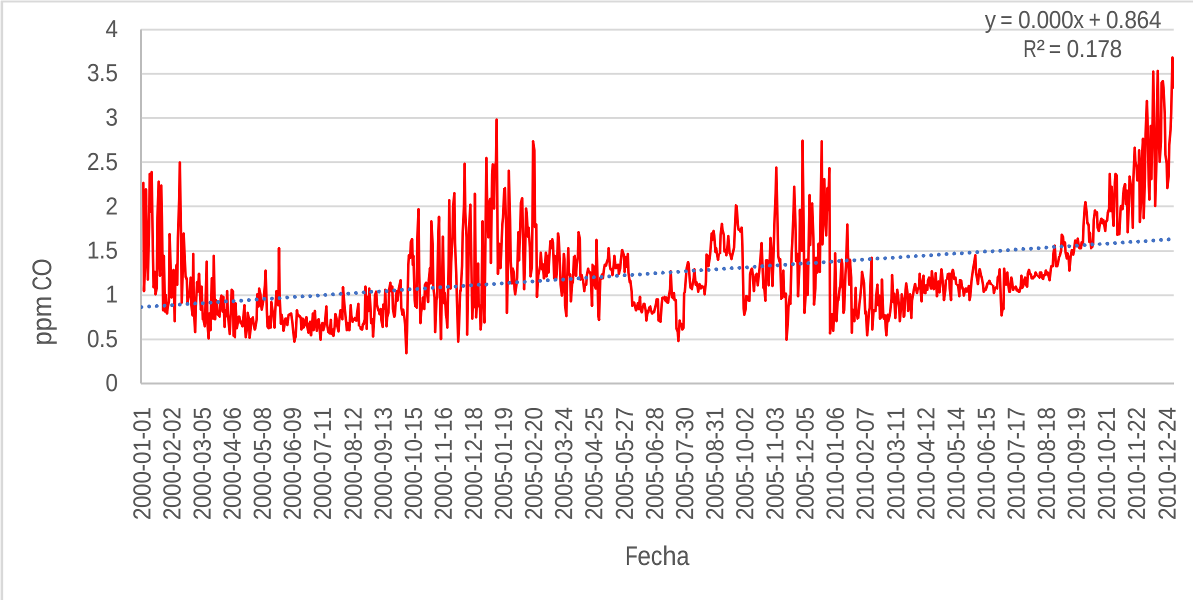

Fig. 20 Daily average CO in ppm in the MMA (2000, 2005, 2010 and 2014)

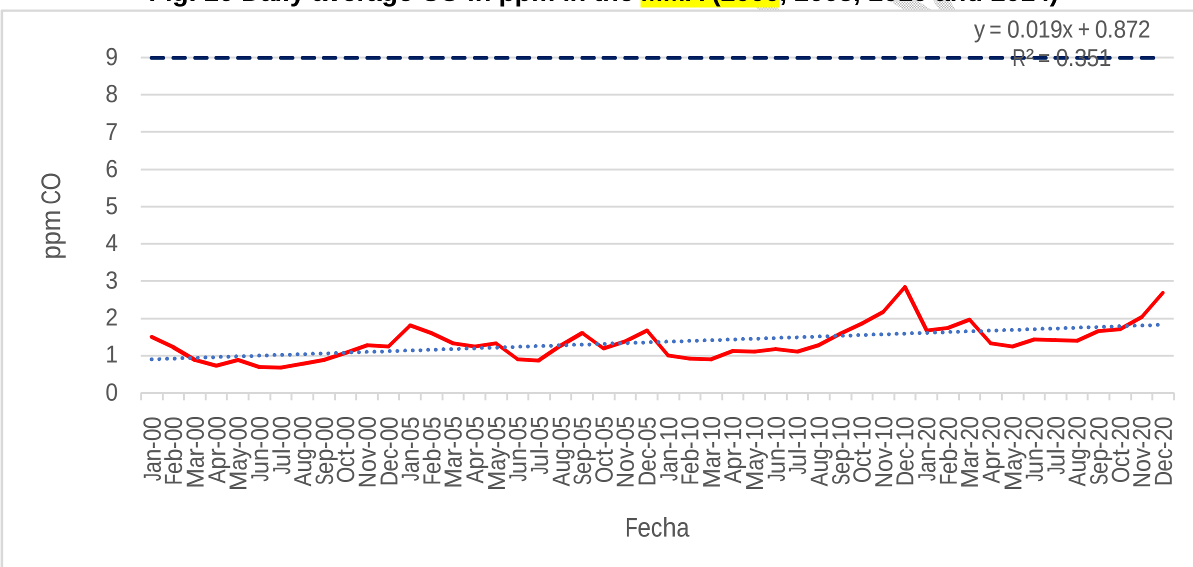

Fig. 21 Average monthly CO in ppm in the MMA (2000, 2005, 2010 and 2014)

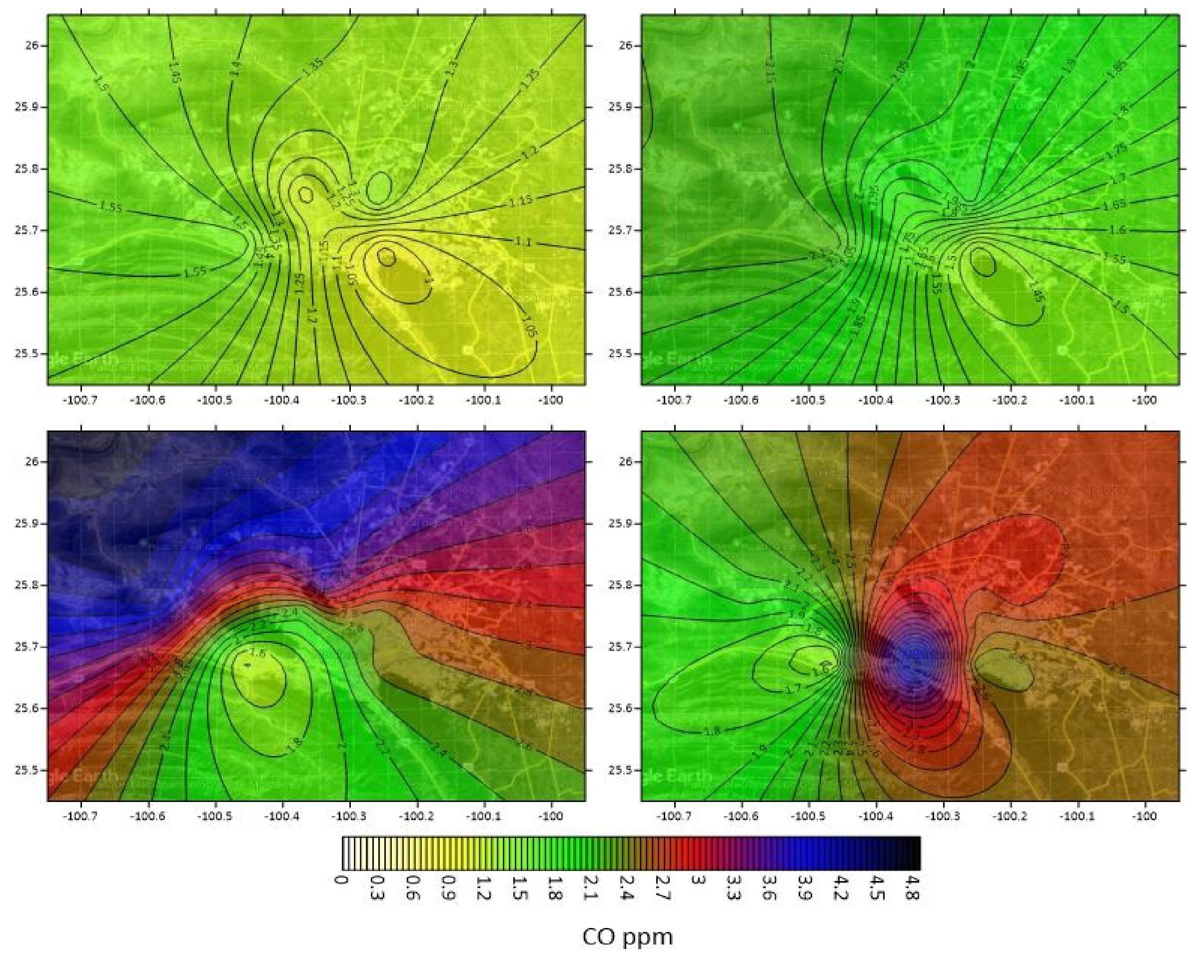

Fig. 22 Temporal space distribution for the highest month of CO (ppm) in the MMA; a) 2000, b) 2005, c) 2010 and d) 2014.