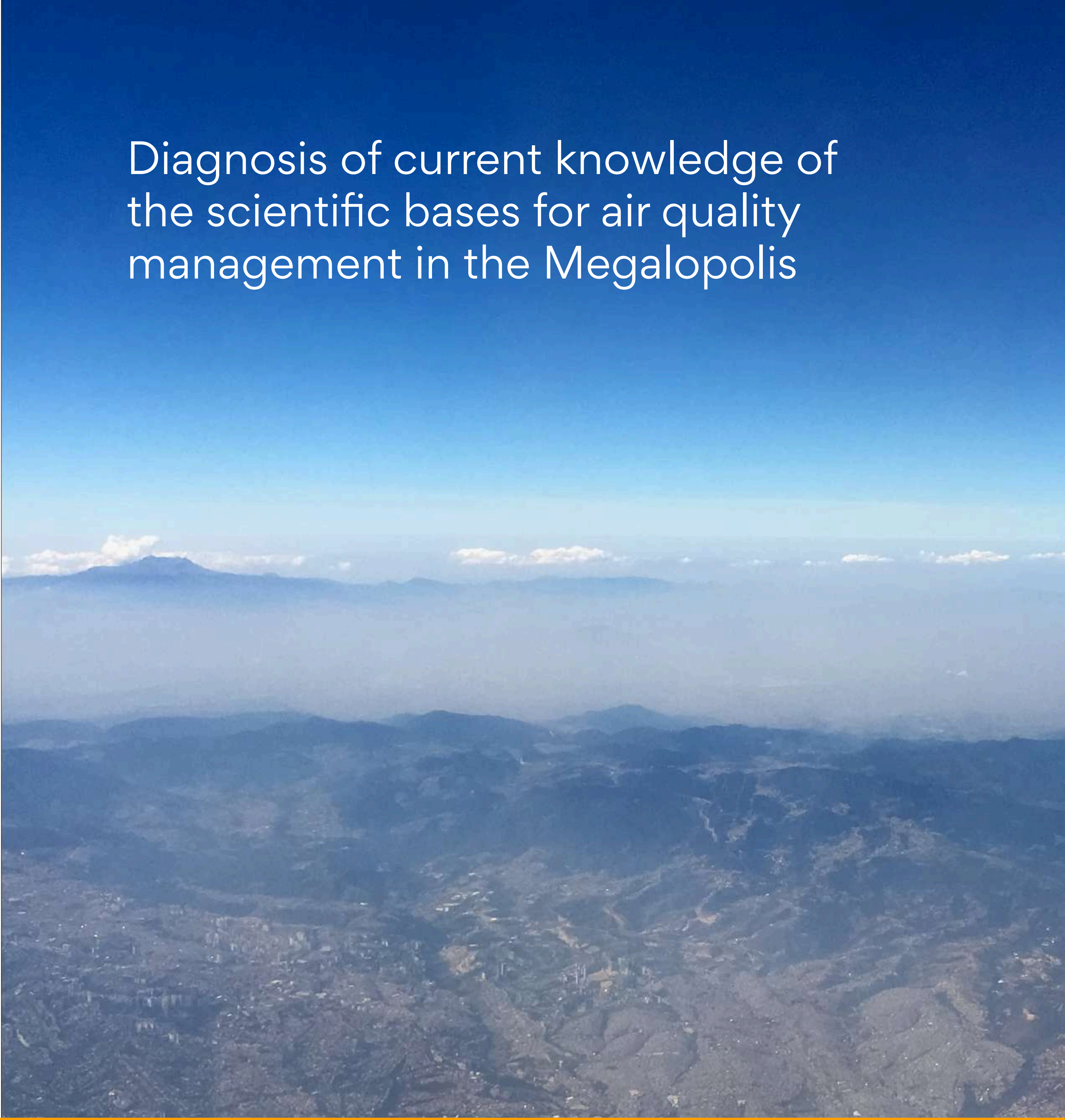
Diagnosis of current knowledge of the scientific bases for air quality management in the Megalopolis



Molina Center for
Energy and the Environment

Diagnosis of current knowledge of the scientific bases for air quality management in the Megalopolis

Luisa T. Molina, Armando Retama and Miguel Zavala

Molina Center for Strategic Studies in Energy and the Environment (MCE2)

Prepared for the

Comisión Ambiental de la Megalópolis (CAMe)

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The document is based in part on the review of the presentations and discussions of the “Virtual Workshop: Diagnosis of current knowledge of the scientific bases for air quality management in the Megalopolis region" that was held on April 21 and 22, 2022, as well as the review of published literature articles and available relevant technical reports.

The virtual workshop was jointly organized by MCE2 and CAMe with the collaboration of the Secretariat of Environment of Mexico City (SEDEMA), Secretariat of Environment of the State of Mexico (SMAGEM), Mexico Ministry of Environment and Natural Resources (SEMARNAT), National Institute of Ecology and Climate Change (INECC), and the Institute of Atmospheric Sciences and Climate Change, National Autonomous University of Mexico (ICAyCC-UNAM). Below is a list of the organizers, moderators, panelists and logistical support personnel.

Organizing Committee: Alejandro Villegas López, Daniel López Vicuña, Hugo Landa Fonseca, Jorge Zavala Hidalgo, Gloria Julissa Calva Cruz, Luis Gerardo Ruiz, Luisa Tan Molina, Olivia Rivera Hernández, Ramiro Barrios Castrejón, Sergio Zirath Hernández, Víctor Hugo Páramo Figueroa.

Moderators: Alejandro Villegas López, Armando Retama, Daniel López Vicuña, Erik Velasco, Gloria Julissa Calva Cruz, Horacio Riojas Rodríguez, Hugo Landa Fonseca, Jorge Zavala Hidalgo, José Agustín García Reynoso, Luisa Tan Molina, Michel Grutter de la Mora, Miguel Zavala, Omar Amador Muñoz, Ramiro Barrios Castrejón, Víctor Hugo Páramo Figueroa,

Panelists: Adalberto Noyola Robles, Adriana Ipiña, Alberto Mendoza Domínguez, Alejandra Méndez Girón, Alejandro Déciga Alcaráz, Alvaro Lomelí Covarrubias, Andrea Burgos Cuevas, Andrea de Vizcaya Ruíz, Angélica Guadarrama Chávez, Armando Retama, Beatriz Herrera Gutierrez, Beatriz Manrique Guevara, Benjamin de Foy, Bernhard Rappenglück, Claudia Inés Rivera Cárdenas, Daniel López Vicuña, Dara Salcedo González, Dzoara Damaris Tejeda Honstein, Erik Velasco, Erika Danaé López Espinoza, Francisco Hernandez Ortega, Graciela Velasco Herrera, Gustavo Enrique Sosa Iglesias, Hugo Landa Fonseca, Iván Yasmani Hernández Paniagua, Jorge Luis García Franco, Jorge Zavala Hidalgo, José Abraham Ortínez Álvarez, José Agustín García Reynoso, José Luis Galindo Cortéz, José Luis Guevara Muñoz, José Luis Texcalac

Sangrador, Karen Elizabeth Nava Castro, Karla Cervantes Martínez, Kate Bloomberg, Laura Noemí Muñoz Benitez, Leonora Rojas Bracho, Leticia Hernandez Cadena, Luis Gerardo Ruiz Suárez, Magali Hurtado Díaz, Manuel Suárez Lastra, Marco Antonio del Prete Tercero, Marco Mora, María del Carmen Calderón Ezquerro, María Eugenia Ibarrarán Viniegra, Mauro Alvarado Castillo, Michel Grutter de la Mora, Miguel Zavala, Mónica del Carmen Jaimes Palomera, Octavio A. Castelán-Ortega, Olivia Rivera Hernández, Omar Amador Muñoz, Oscar Peralta Gutiérrez, Patricia Camacho Rodríguez, Ramiro Barrios Castrejón, Ricardo Torres Jardón, Rodolfo Iniestra Gómez, Rodolfo Sosa Echeverría, Salvador Blanco Jiménez, Salvador Medina Ramírez, Sergio Israel Mendoza, Sergio Zirath Hernández Villaseñor, Stephan Brodziak de los Reyes, Stephanie Montero Bending, Verónica Garibay, Víctor Almanza Veloz, Victor Torres Meza, Violeta Mugica Álvarez, Zuhelen Verónica Padilla Barrera.

Logistical Support: Ana Lilia Ubaldo Moreno, Eduardo Alberto Durán Rodríguez, Elizabeth Méndez Márquez, Israel Hupio Montesinos, Jennifer Sandra García Escalante, Julia Jiménez Bejarano, Mónica Palomero Rivero, Ricardo Daniel Ramírez Pérez, Valeria Navarro Pérez de León, Yeni Solís Reyes.

ACRONYMS, ABBREVIATIONS AND CHEMICAL SYMBOLS

$\mu g/m^3$	Microgram per cubic meter
AERAS	*AERosoles AtmosféricoS*
AOD	Aerosol optical depth
ASEA	*Agencia de Seguridad, Energía y Ambiente* (Security, Energy and Environment Agency)
AQFS-Mex	Air Quality Forecasting System – Mexico City
BC	Black carbon
BOD	Biochemical oxygen demand
BrC	Brown carbon
BUAP	*Benemérita Universidad Autónoma de Puebla*
CAA	Clean Air Act
CAM	*Comisión Ambiental Metropolitana*
CAMe	*Comisión Ambiental de la Megalópolis*
CARB	California Air Resources Board
CCAC	Climate and Clean Air Coalition
CDMX	*Ciudad de México*
CENAPRED	*Centro Nacional de Prevención de Desastres*
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COVID-19	Coronavirus disease of 2019
Cr	Chromium
Cu	Copper
DGGCARETC	*Dirección General de Gestión de la Calidad del Aire y Registro de Emisiones y Transferencia de Contaminantes*
DGIELGCA	*Dirección General de Industria, Energías Limpias y Gestión de la Calidad del Aire* (General Directorate of Industry, Clean Energy and Air Quality Management)
DMCA	*Dirección de Monitoreo de la Calidad del Aire* (Air Quality Monitoring Directorate of Mexico City)
EC	Elemental carbon
EPA	Environmental Protection Agency
FTIR	Fourier-transform infrared spectroscopy
GAW	Global Atmospheric Watch
GHG	Greenhouse gas
GMAO	Global Modeling and Assimilation Office

GTZ	*Agencia Alemana de Cooperación Técnica* (German Technical Coorperation Agency)
GWP	Global warming potential
H_2O_2	Hydrogen peroxide
HCHO	Formaldehyde
HERMES	High-Elective Resolution Modeling Emission System
HFC	Hydrofluorocarbons
Hg	Mercury
HNO_2	Nitrous acid
HNO_3	Nitric acid
IASI	Infrared Atmospheric Sounding Interferometer
ICAyCC	*Instituto de Ciencias de la Atmósfera y Cambio Climático* (Institute of Atmospheric Sciences and Climate Change)
ICM	*Iniciativa Climática de México*
IE-ZMVM	*Inventario de Emisiones de Contaminantes Criterio de la ZMVM* (Inventory of Criteria Pollutant Emissions of Mexico City Metropolitan Area)
IEA	International Energy Agency
IMADA-AVER	Investigación sobre Materia Particulada y Deterioro Atmosférico-Aerosol and Visibility Evaluation
INE	Instituto Nacional de Ecología
INECC	*Instituto Nacional de Ecología y Cambio Climático* (National Institute of Ecology and Climate Change)
INEGI	*Instituto Nacional de Estadística y Geografía* (National Institute of Statistic and Geography)
INEGYCEI	*Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero* (Mexico National Inventory of Greenhouse Gas Emissions and Compounds)
INEM	*Inventario Nacional de Emisiones de México* (Mexico National Emissions Inventory)
INSP	*Instituto Nacional de Salud Pública* (National Institute of Public Health)
IPCC	International Panel on Climate Change
JICA	Japan International Cooperation Agency
LGCC	*Ley General de Cambio Climático* (General Law of Climate Change)
LGEEPA	*Ley General del Equilibrio Ecológico y la Protección al Ambiente* (General Law of Ecological Equilibrium and Environmental Protection)
LIDAR	Light detection and ranging
LPG	Liquified petroleum gas
LTMCE2	LTM Center for Energy and the Environment
MARI	Mexico City Air Quality Research Initiative
MCCM	Multiscale Climate Chemistry Model
MCE2	Molina Center for Strategic Studies in Energy and the Environment

MCMA	Mexico City Metropolitan Area
MCMA-2003	Mexico City Metropolitan Area-2003 Campaign
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MILAGRO	Megacity Initiaitve: Local And Global Research Observations
MIT	Massachusetts Institute of Technology
MOVES	Motor Vehicle Emissions Simulator
Mt	Millions of tons or Megatons
NASA	National Aeronautics and Space Administration
NDC	National Determination Contribution
NH_3	Ammonia
Ni	Nickel
NO	Nitric oxide
NO_2	Nitrogen dioxide
N_2O	Nitros oxide
NOx	Nitrogen oxides
NOM	*Normas Oficiales Mexicanas* (Official Mexico Standards)
NRC	National Research Council
O_3	Ozone
OH	Hydroxyl radical
PAN	Peroxyacetyl nitrate
Pb	Lead
PBL	Planetary boundary layer
PCAA	*Programa de Contingencias Ambientales Atmosféricas*
PEMEX	Petróleos Mexicanos
PFC	Perfluorocarbons
$PM_{0.1}$	Particles with diameters of 0.1 micrometers or smaller
PM_{10}	Particles with diameters of 10 micrometers or smaller
$PM_{2.5}$	Particles with diameters of 2.5 micrometers or smaller
ppm	Parts per million
PPRECCA	*Programa para Prevenir y Responder a Contingencias Ambientales Atmosféricas*
ProAire	*Programa Para Mejorar la Calidad del Aire* (Air Quality Improvement Program)
Pt	Platinum
PVVO	*Programa de Verificación Vehicular Obligatorio* (Obligatory Vehicle Verification Program)
RAMA	*Red Automática de Monitoreo Atmosférico* (Automatic Atmospheric Monitoring Network)

SEDATU	*Secretaría de Desarrollo Agrario, Territorial y Urbano* (Ministry of Agrarian, Territorial and Urban Development)
SEDEMA	*Secretaría del Medio Ambiente de la Ciudad de México* (Secretariat of Environment of Mexico City)
SEMARNAT	*Secretaría de Medio Ambiente y Recursos Naturales* (Ministry of Environment and Natural Resources)
SEMARNATH	*Secretaría de Medio Ambiente y Recursos Naturales del Estado de Hidalgo* (Secretariat of Environment and Natural Resources of the State of Hidalgo)
SF_6	Sulfur hexafluoride
SICT	*Secretaría de Infraestructura, Comunicaciones y Transportes* (Ministry of Infrastructure, Communications and Transportation)
SIMAT	*Sistema de Monitoreo Atmosférico de la Ciudad de México* (Atmospheric Monitoring System of Mexico City)
SINAICA	*Sistema Nacional de Información de Calidad del Aire* (National Air Quality Information System)
SLCF	Short-lived Climate Forcers
SLCP	Short-lived Climate Pollutants
SMAGEM	*Secretaría del Medio Ambiente del Gobierno del Estado de México* (Secretariat of Environment of State of Mexico)
SMN	*Servicio Meteorológico Nacional* (National Meteorological Service)
SNAP	Supporting National Action and Planning on Short-Lived Climate Pollutants
SO_2	Sulfur dioxide
SUV	Sport Utility Vehicle
TAG-GC/MS	Thermal Desorption Aerosol - Gas Chromatography /Mass Spectrometer
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TROPOMI	TROPOspheric Monitoring Instrument
TSP	Total suspended particle
UHI	Urban Heat Island
UNAM	*Universidad Nacional Autónoma de México* (National Autonomous University of Mexico)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
VOC	Volatile organic compound
WHO	World Health Organization
WMO	World Meteorological Organization
WRF-ARW	Weather Research and Forecasting - Advanced Research
WRF-Chem	Weather Research and Forecasting with Chemistry
WWTP	Wastewater treatment plant
Zn	Zinc

EXECUTIVE SUMMARY

1. INTRODUCTION

1.1. Background

With more than twenty-one million inhabitants, the Mexico City Metropolitan Area (MCMA) is one of the largest megacities in the world and the most populous metropolitan area in North America. Mexico City and its metropolitan have undergone massive transformation in urbanization and demographics throughout its history. The population went from less than three million inhabitants in 1950 to more than eighteen million in the year 2000, which corresponds to an approximate increase of six times in fifty years. The continuous urban expansion went from 690 km^2 to ~ 1500 km^2 during the same period, pushing the urban zone beyond the limit of the Federal District (now Mexico City) towards the State of Mexico, as well as some parts of the State of Hidalgo, integrating what is known as the Mexico City Metropolitan Area. The population growth rate of Mexico City has remained stable since the year 2000, while the urban population of the State of Mexico continues to increase, therefore, more municipalities of the State of Mexico have been added to the MCMA over the years. Currently, the metropolitan area has more than 21.7 million inhabitants, of which 9.0 million live in Mexico City and 12.6 million in fifty-nine municipalities of the State of Mexico and the municipality of Tizayuca, Hidalgo. The neighboring metropolitan areas (Puebla, Tlaxcala, Cuernavaca, Pachuca, and Toluca) have also shown increasing population growth. This multiple expansion has produced a contiguous urban complex known as the Mexico "Megalopolis" that include Mexico City and the municipalities from five contiguous states, Mexico, Puebla, Tlaxcala, Morelos, and Hidalgo, with an estimated population of about thirty-five million in the urbanized areas. For environmental management purposes, the state of Querétaro is also considered as part of this Megalopolis. Figure 1 shows a map of the Megalopolis.

The combination of rapid population growth, urban sprawl, increasing energy consumption and motorization, as well as a high-altitude basin surrounded by mountains and intense solar radiation led to severe air pollution problems for Mexico City metropolitan area in the 1980s. In response to growing public concern about poor air quality, the Mexican government announced emission reduction actions, strengthened the legal framework that defined responsibilities at federal, state, and local government levels, and established several administrative agencies to address environmental issues, including the Metropolitan Environmental Commission (CAM, *Comisión Ambiental Metropolitana*) in 1996 to coordinate the various levels of government dealing with metropolitan environmental problems. Subsequently, CAM was replaced in 2013 by the Environmental Commission of the Megalopolis (CAMe, *Comisión Ambiental de la Megalopolis*) to address the environmental issues in the Megalópolis.

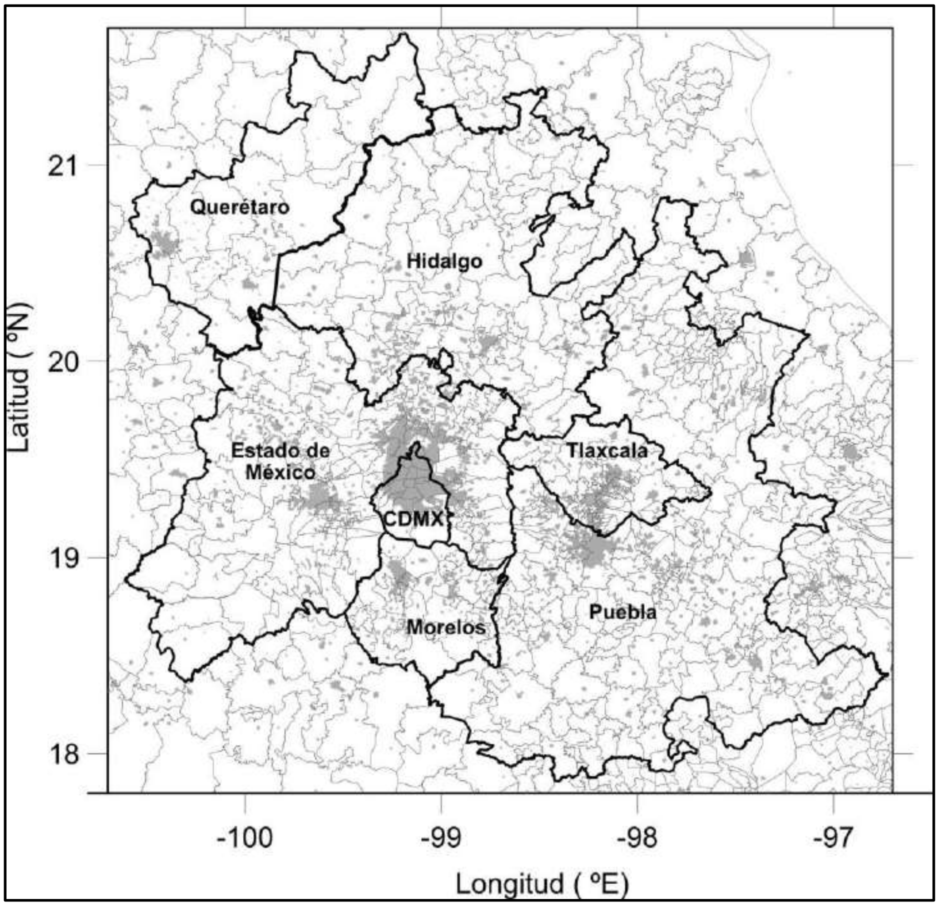

Figure 1. Map of the Megalopolis, the state limits are indicated with a thick black line, while the municipal ones with thinner lines, the urbanized areas are highlighted with a gray shading.

Starting in the 1980s, efforts were made to establish comprehensive air quality management programs based on scientific, technical, social, and political considerations; the MCMA managed to drastically reduce air pollutants and improve public health. At the beginning of this century, atmospheric concentrations of lead (Pb), sulfur dioxide (SO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2) fell drastically to levels below the values established by the Official Mexican Standards (NOM, *Normas Oficiales Mexicanas*) for air quality. The concentrations of ozone (O_3), PM_{10} (particles with diameter of 10 micrometers and smaller) and $PM_{2.5}$ (particles with diameters of 2.5 micrometers and smaller) also decreased, but at levels higher than the respective standards.

The air quality monitoring systems of the entities that surround Mexico City report concentrations of O_3, PM_{10} and $PM_{2.5}$ that frequently exceed the limit values of the NOM. The average concentrations of some urban centers equal or exceed those observed in Mexico City, displaying the regional scale of air quality deterioration. Detailed information on the situation of air quality in the entities of the Megalopolis can be found in the annual air quality reports of the National Institute of Ecology and Climate Change (INECC, *Instituto Nacional de Ecología y Cambio Climático*). Figures 2 to 4 show the comparison between the maximum concentrations reported by the different monitoring networks of the CAMe region in 2020 and the NOM limit values for O_3, PM_{10} and $PM_{2.5}$, respectively.

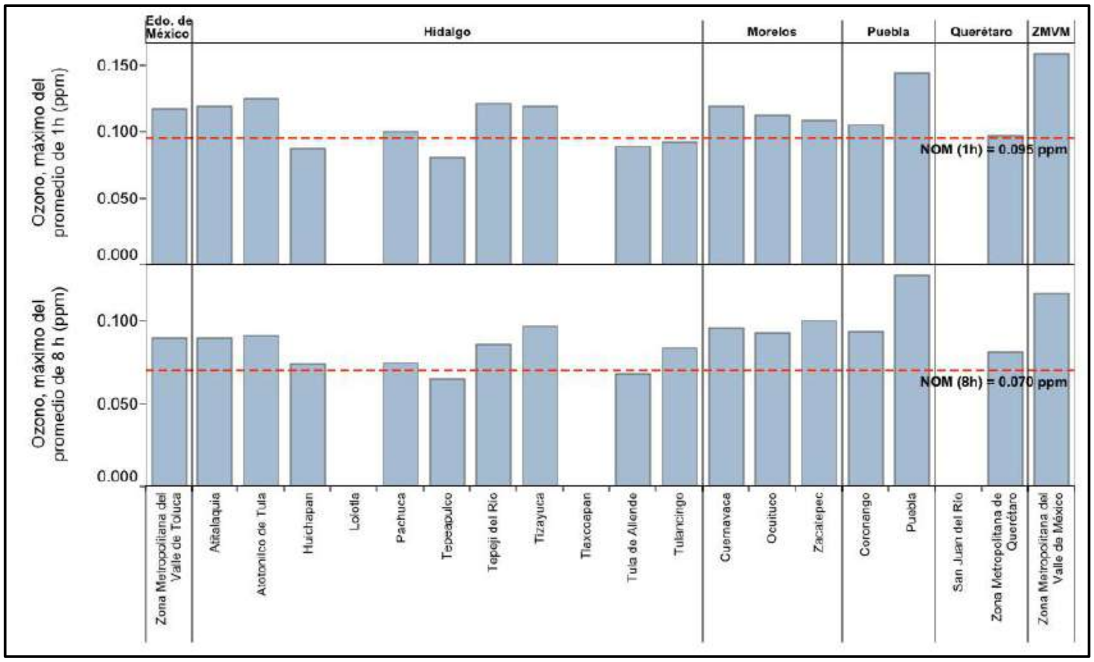

Figure 2. Comparison of the maximum O_3 concentrations for the 1-hour (upper) and 8-hour (lower) average reported by the different monitoring networks in the Megalopolis region during 2020. The limit values of NOM-020-SSA1-2021 are indicated with the dashed red line (Source: prepared with data from INECC used in the 2020 National Air Quality Report.)

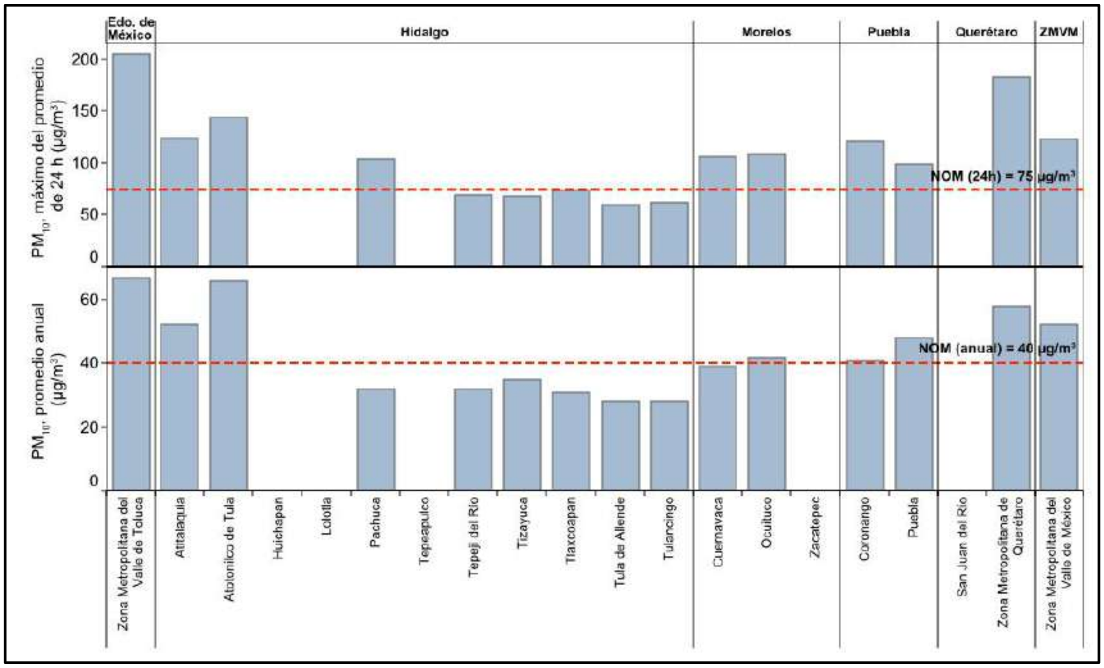

Figure 3. Comparison of the maximum PM_{10} concentrations for the 24-hour (upper) and annual (lower) average reported by the different monitoring networks in the Megalopolis region during 2020. The limit values of NOM-025-SSA1-2021 are indicated with the dashed red line (Source: prepared with data from INECC used in the 2020 National Air Quality Report.)

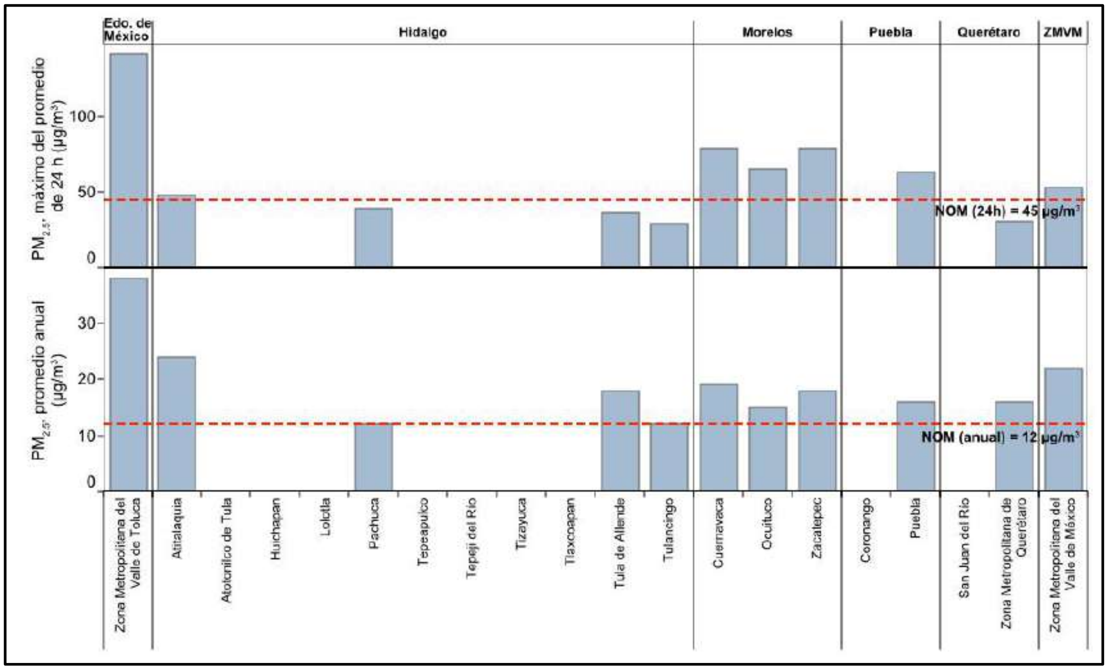

Figure 4. Comparison of the maximum $PM_{2.5}$ concentrations for the 24-hour average (upper) and annual average (lower) reported by the different monitoring networks in the Megalopolis region during 2020. NOM-025 limit values -SSA1-2021 are indicated with the dashed red line (Source: prepared with data from INECC used in the 2020 National Air Quality Report.)

In recent years, episodes with high concentrations of O_3 and $PM_{2.5}$ have been recorded in the MCMA and other entities of the Megalopolis associated with unfavorable meteorological events for the dispersion of pollution. In addition, regional wildfires intensified during periods of increasingly frequent and intense droughts have induced severe episodes of particulate pollution. The lockdown measures enacted in response to COVID-19 pandemic demonstrated that even drastic reductions in economic activities and vehicular traffic have relatively minor impacts on the decrease in O_3 levels in the Megalopolis. This experience has profound implications for air quality management, since basic control policies are aimed to reduce emissions from traffic and industry to protect public health and the environment.

In order to guide the design of new air quality improvement policies in the Megalópolis region, locally generated and updated scientific information is required on changes in emission profiles resulting from new regulatory measures and technological improvements, changes in urban climate caused by increasing urbanization, and changes in the atmospheric physical and chemical processes under a changing climate.

To achieve this objective, the Molina Center for Strategic Studies in Energy and the Environment (MCE2) produced this document. The text includes a diagnosis of the current technical and scientific knowledge on emerging sources of emissions, air quality monitoring and measurements in the Megalópolis, changes in the atmospheric chemistry over the years, the impacts of pollutants on public health and climate change, and the impacts of COVID-19 pandemic on air quality.

The document is based on the results of the review and analysis of recently published scientific articles and relevant technical reports, as well as integrating the key findings of the "Virtual Workshop: Diagnosis of current knowledge of the scientific bases for air quality management in the Megalopolis region" ("*Taller virtual: Diagnóstico sobre el conocimiento actual de las bases científicas para la gestión de la calidad del aire en la región de la Megalópolis,"* hereinafter "the Virtual Workshop"), which was held on April 21-22, 2022.

The virtual workshop was jointly organized by the MCE2 and the Executive Coordination of CAMe, with the collaboration of the Secretariat of Environment of Mexico City (SEDEMA, *Secretaría del Medio Ambiente de la Ciudad de México*), the Secretariat of Environment of the State of Mexico (SMAGEM, *Secretaría del Medio Ambiente del Gobierno del Estado de México*), the Ministry of Environment and Natural Resources (SEMARNAT, *Secretaría de Medio Ambiente y Recursos Naturales*), INECC, and the Institute of Atmospheric Science and Climate Change at the National Autonomous University of Mexico (ICAyCC-UNAM, *Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México*).

The objective of the Virtual Workshop was to identify recent advances and gaps in the scientific and technical knowledge on air quality, and the challenges faced by decision makers in the implementation of policies on this matter. The workshop participants included specialists in air pollution issues from academic, governmental and civil society organizations, who presented and discussed the results of their scientific and technical studies, as well as authorities from the federal and local agencies who shared their knowledge and the barriers in implementing air quality improvement policies. The agenda, list of panelists, and summary of the presentations and discussions are available as supplement (Spanish) to this document.

1.2. Role of science in air quality management

Scientific research has played an important role in helping the environmental authorities of the MCMA to characterize the emission sources of polluting species, their transport and transformation in the atmosphere, their effects on human health and the environment, and the identification of effective emission reduction strategies.

As shown in Figure 5, air quality management is an iterative and dynamic process represented as a cycle of inter-related elements. Typically, the process starts with a government institution establishing air quality goals, targets, and standards, and setting threshold concentrations for key pollutant species that will protect public health and the environment. Air quality managers, through the application of various assessment tools, including emission inventories, air quality monitoring and modeling, will need to determine emission reductions needed to meet the standards and objectives. During the development of control strategies, air quality managers should include the required budget, implementation mechanisms, the agencies responsible for the actions and a schedule of compliance and implementation plans. To achieve the required reductions goals, they must implement the proposed programs, enforce the rules and regulations, maintain an ongoing evaluation of the effectiveness of the strategies, and measure the progress towards meeting the air quality goals. A key element in this process is the contribution of t science and technology throughout the cycle through monitoring, analysis, research and development, to provide the air quality managers with fundamental knowledge to make informed decisions.

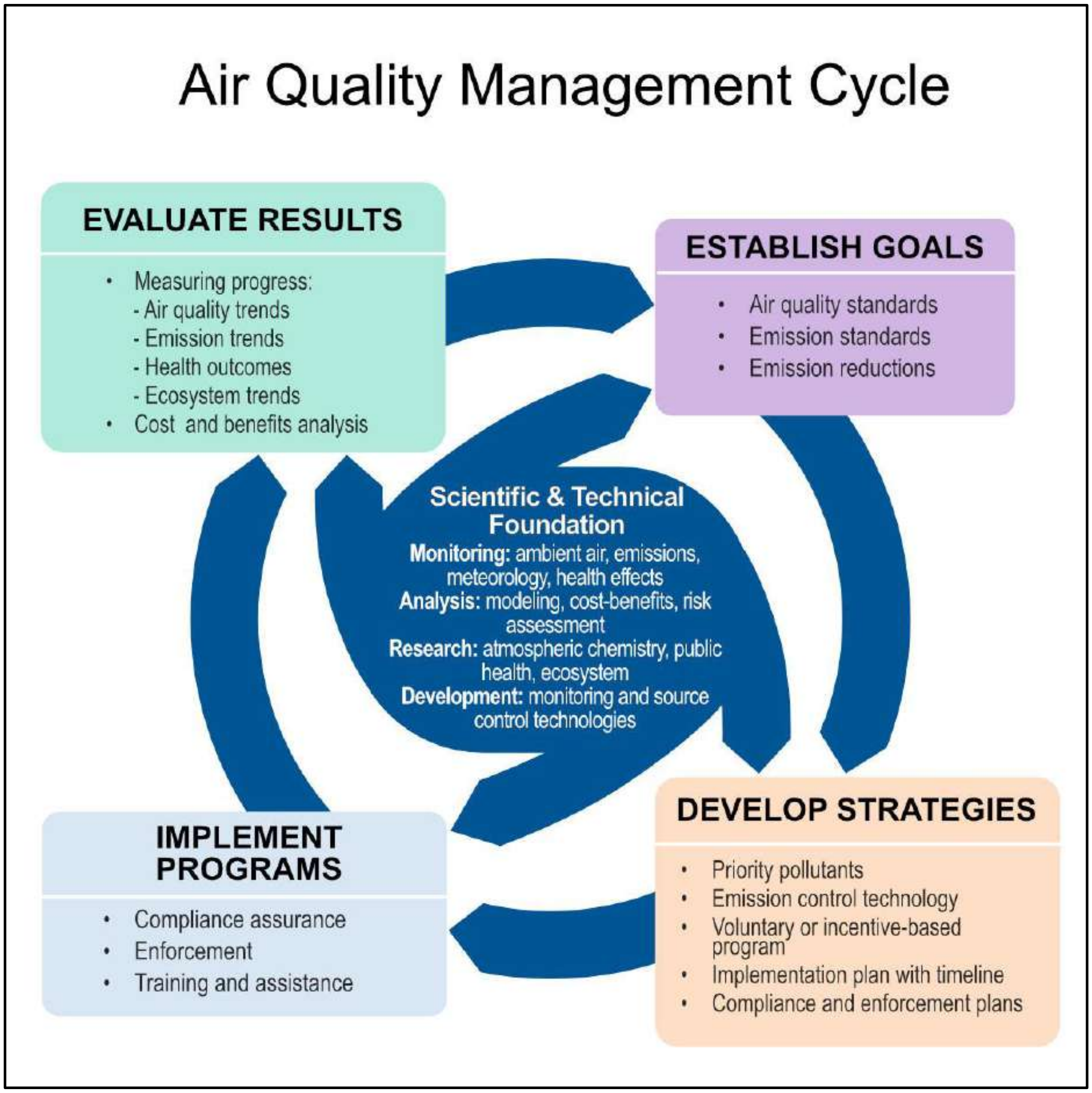

Figure 5. The air quality management process (Adapted from NRC, 2004 and Bachman, 2007).

Scientific studies, such as the integrated assessment of air quality in Mexico City carried out in 2000 (*Programa Estratégico de Gestión Integral de la Calidad del Aire en el Valle de México para el período 2001-2010*), and the intensive field measurement campaigns, MARI (Mexico City Air Quality Research Initiative) in 1994, IMADA-AVER (*Investigación sobre Materia Particulada y Deterioro Atmosférico*, IMADA-AVER) in 1997, the MCMA-2002 and MCMA-2003 campaigns, and MILAGRO (Megacity Initiative: Local and Global Research Observations) in 2006, provided comprehensive information on the emissions and the transport and transformation of pollutants in the atmosphere overlying the MCMA, as well as their impact on a regional scale. The results significantly improved our understanding of the meteorological and photochemical processes contributing to the formation of O_3, secondary aerosols, and other pollutants. Key scientific findings and policy implications were incorporated in the design of previous comprehensive air quality improvement programs. Except for some special studies conducted by Mexico City Atmospheric Monitoring System (SIMAT, *Sistema de Monitoreo Atmosférico de la Ciudad de México*), INECC, MCE2, universities, and independent researchers, since the MILAGRO campaign, relatively few studies have been carried out in the MCMA and other region of the Megalopolis.

This document describes the current scientific understanding of the air quality and management in the MCMA and other regions of the Megalopolis. Chapter 2 provides a detailed description of the current state of knowledge on air quality monitoring, while emission characterization, atmospheric scientific research, and health impact studies are presented in Chapters 3, 4, and 5, respectively. Chapter 6 describes some of the major air quality management programs implemented in the MCMA and the Megalopolis region. The document concludes by summarizing the challenges and lessons learned in the implementation of emissions control policies in the Megalopolis region (Chapter 7), based on the most recent information available.

2. KEY FINDINGS

2.1. Air quality monitoring in the Megalopolis

The entities that make up the Megalopolis have air quality monitoring systems equipped with instruments for the continuous measurement of criteria pollutants. Among them is SIMAT, which concentrates the largest infrastructure and technical capacity with adequate spatial coverage for Mexico City and part of the metropolitan area, and is designed to serve various monitoring objectives. The quality of the data generated meets the technical standard of environmental management as well as for scientific research. The rest of the entities of the Megalopolis have monitoring systems, most of their monitoring stations are located in the capital cities and some main urban settlements. A large part of the territory of the entities and inter-urban extensions does not have air quality data. In most cases, the operation is the responsibility of the state authorities with little involvement from the municipal authorities.

Experience shows that there is a correlation between age and complexity of monitoring systems, where older systems have a greater number of stations, more and better equipment, and experienced personnel, as is the case with systems in the metropolitan areas of Toluca and Puebla. The most recent systems, such as those in Morelos and Tlaxcala, are still in the process of consolidation. There is also a relationship between data quality and the level of maturity and capabilities of the network. Unfortunately, with the exception of the data generated by SIMAT, there are doubts about the quality of the data generated by the other systems, which calls into question their purpose. The lack of an adequate budget for operation and maintenance activities, the limitations in the renewal of equipment, the lack of trained personnel, and the disparity in the quality of the data are important aspects that require immediate attention. In recent years, CAMe has promoted the acquisition of new instrumentation for the reinforcement of the local networks.

In terms of air quality monitoring, INECC has the infrastructure and knowledge to carry out training, technical audits, and the transfer of standards, in addition to conduct research projects on various environmental topics. The experience and capacity of INECC could be used to correct the identified limitations.

The dissemination of data on the state of air quality is carried out through official communication media such as the websites of local environmental authorities, the National Air Quality Information System (SINAICA, *Sistema Nacional de Información de Calidad del Aire*), mobile applications and, in some cases, through social networks. The use of the Air and Health Index (*Índice Aire y Salud*) integrates the reports of the different entities; however, it is essential to advance in the harmonization of the review and validation criteria of the data, as well as their timely publication.

2.2. Emissions inventory

Since the early 1990s, SEDEMA has published the Emissions Inventory for the Metropolitan area of the Valley of Mexico (IE-ZMVM, *Inventario de Emisiones para la Zona Metropolitana del Valle de México*) every two years, which covers four general categories: Point sources (industry), Area sources (services and residential), Mobile sources (transportation), and Natural sources (vegetation and soil). The most recent version of the IE-ZMVM is available for the base year 2018 (the 2020 emissions inventory is being prepared and will be published during the second half of 2023), which also includes emissions of toxic pollutants, black carbon (BC) and greenhouse gases (GHG), as well as the diurnal and spatial variability of emissions. The estimates from this inventory were used to inform emission reduction strategies and the prioritization of the measures and actions of ProAire 2021-2030.

At the federal level, the General Directorate of Industry, Clean Energies and Air Quality Management (DGIELGCA, *Dirección General de Gestión de la Calidad del Aire y Registro de Emisiones y Transferencia de Contaminantes*) of SEMARNAT is responsible for developing the National Emissions Inventory of Mexico (INEM, *Inventario Nacional de Emisiones de México*), the most recent version is for the base year 2016. In preparing the INEM, it collaborates with other agencies associated with the Federal Government and the environmental authorities of the states and municipalities, as well as with academic, research, and non-governmental organizations. Currently, DGIELGCA collaborates with CAMe in the preparation of the inventory of on- road mobile sources for the Megalopolis, base year 2018, which includes updating the MOVES Mexico model and the incorporation of motorcycles; they also participate in the regional emissions inventory that harmonizes the criteria pollutants by source type. It is important that the experience acquired in the preparation of emission inventory is transferred to the technical personnel of the entities. At the Megalopolis level, the need to have updated emission factors for the vehicle fleet circulating in the region was identified, in addition to increasing the spatial resolution of the emissions inventory and including emerging sources of pollution. Currently, only the MCMA has a high resolution emissions inventory and maintains a continuous effort to identify and quantify new emission sources, considering the use of observations in estimating emission profiles and their temporal variability. The INEM is making efforts to build an updated inventory with spatial and temporal resolutions in all sources and ready for modeling.

In addition to INEM, INECC is responsible for developing the National Inventory of Emissions of Greenhouse Gases and Compounds (INEGYCEI, *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*), which is an essential environmental management tool for developing policies related to mitigating climate change and is part of international commitments that Mexico presented to the United Nations Framework Convention on Climate Change (UNFCCC). The INEGYCEI is developed following the criteria established by the Intergovernmental Panel on Climate Change (IPCC) and is periodically updated to be presented in the National Communications of Mexico before the UNFCCC. The inventory contains estimates of emissions and removals of greenhouse gases and compounds from energy, industrial processes and product use, agriculture, forestry and other land uses, and waste. The most recent version of the INEGYCEI includes estimates of carbon dioxide (CO_2),, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and BC emissions for the period 1990 to 2019. Mexico was the first country to commit to reducing BC as part of its commitment to the UNFCCC Conference of the Parties (COP21) held in Paris in December 2015. During COP 26 in Glasgow, Scotland, in November 2021, Mexico joined more than 100 countries in committing to reduce CH_4 emissions by 30% by 2030. Results from field studies conducted in Mexico to characterize CH_4 emissions from wastewater treatment plants and enteric fermentation of livestock indicated that the IPCC methodologies represent an inaccurate tool for estimating local greenhouse gases; it is important to determine specific emission factors to more accurately estimate GHG emission inventories. Similarly, field studies showed the importance of obtaining BC emission factors and associated pollutants under real operating conditions from on- and off-road vehicles, brick kilns, and stoves, to improve emission estimates (see Chapter 4, Section 4.5).

2.3. Air quality modeling and forecasting

Numerical modeling is an essential tool to support decision makers in the design of air quality policies and in the evaluation of control measures in present and future climate and emission scenarios, as well as air quality forecasting. The real-time air quality forecast plays a very important role in informing the population about potentially harmful concentrations of pollutants such as O_3, PM_{10}, $PM_{2.5}$ and NO_2. This information allows the government and the public to develop prevention measures, such as restricting vehicle circulation to limit emissions and minimizing outdoor activities to limit exposure to unhealthy levels of air pollution.

Currently, the Mexico City government has implemented an air quality forecast system to alert the public about the possible presence of high O_3 and $PM_{2.5}$ pollution 24 hours in advance, and for the evaluation of emission reduction policies to improve air quality and other co-benefits. The system performs well in forecasting maximum O_3 concentrations, however, it has difficulties in forecasting very high pollution events that usually trigger atmospheric contingencies in the MCMA, and it performs less well for forecasting $PM_{2.5}$. The ICAyCC-UNAM has a 72-hour forecast model for criteria pollutants covering the cities of Toluca, Cuernavaca, Tlaxcala, Puebla and Mexico City. Similar to the performance of the SEDEMA forecast system, the ICAyCC-UNAM model underestimates concentrations during high O_3 pollution events.

At the Megalopolis level, there are still substantial challenges for the implementation of a forecast system due to the need for better data for both monitoring and inventory of emissions, as well as infrastructure and qualified technical personnel. With the collaboration of the ICAyCC-UNAM, CAMe intends to develop and implement a modeling and forecasting system, initially with an air quality forecast course-workshop aimed at the entities of the Megalopolis.

2.4 Atmospheric scientific research in the Megalopolis

The study of atmospheric processes constitutes a fundamental activity to understand the sources, transformations and impacts of air pollution and to evaluate the best mitigation options. In the MCMA, the physical and chemical processes that control the emission, transformation, and transport of atmospheric pollutants were studied in great detail during the intensive collaborative field studies, MCMA-2002/2003 and MILAGRO-2006 campaigns. Since then, relatively few field studies have been conducted in the MCMA, while there is almost no research in the other region of the Megalopolis. Most of these studies have been conducted by SIMAT, universities, MCE2, INECC, and independent researchers, including characterization of volatile organic compounds (VOCs), O_3 production, SO_2, reactive atmospheric nitrogen compounds, aerosol composition and optical properties, bioaerosols, toxic metals, short-lived climate forcers (BC and CH_4), personal exposure, environmental epidemiology and toxicology, as well as urban meteorology.

A review of the atmospheric scientific research, which is described in greater detail in Chapters 2 and 4, shows that no substantial progress has been made in improving air quality in the MCMA in the last decade. Concentration trends of O_3 and $PM_{2.5}$ have stalled, and recent severe air pollution episodes suggest that the production of secondary pollutants has increased under an expanding urban sprawl, a growing vehicular fleet, and the increasing relevance of emerging sources of VOCs. Given the continuous emissions of large amounts of pollutants, the changing climate can trigger serious pollution events. The severe episodes of O_3 air pollution that occurred in 2016 were associated with regional meteorological events, which suppressed the ventilation of the city basin and affected the evolution of the planetary boundary layer, atmospheric recirculation, and accumulation of locally produced and emitted pollutants. The particulate episodes in May 2019 were caused by emissions from forest fires inside and outside the Megalopolis, which could become more intense and frequent due to climate change.

The atmosphere of the MCMA has experienced progressive warming in recent decades, possibly because of the synergistic interaction between increased land cover modification, new material used for construction, anthropogenic heat, and changes in temperature associated with global climate change. A similar growing trend in ambient temperatures have been observed in other entities of the Megalopolis. An increasing trend in the intensity of ultraviolet (UV) solar radiation has been identified also in the MCMA, which could intensify the production of secondary pollutants, as well as increase risks to human health, for example, cataracts, skin cancer. These aspects are described in more detail in Chapter 4, Section 4.4.

An unintended consequence related to the COVID-19 pandemic lockdown was the reduction in emissions from automobiles, some industrial sectors and commercial activities, on a scale unprecedented in Mexico, offering atmospheric scientists and air quality managers a unique opportunity to study the effects of extraordinary reductions in anthropogenic activities on air quality. Assessment of air quality data in the MCMA and modeling studies during the pandemic confirmed that the application of the restrictions led to reductions in the average levels of CO, SO_2, NO_2, PM_{10}, and $PM_{2.5}$ in the ambient air, while O_3 concentrations were observed to increase. The experience during the restrictions confirmed the role of vehicle emissions, mainly private vehicles, and industrial emissions in the deterioration of air quality, but also raised questions about the effectiveness of the mitigation strategies and current management scheme. It is not enough to control emissions from vehicular traffic and manufacturing activities, a comprehensive regulation of precursors gases from all possible emission sources must be considered. A more detailed analysis of what happened during the pandemic is urgently needed and lessons drawn that contribute to the identification of new policies complementing the proposal in ProAire 2021-2030 (see Chapter 4, Section 4.7).

Scientific knowledge promotes the effective management of air quality through the identification of priority sources, the interpretation of the transport and transformation processes of pollutants and the guide for the design of control actions. Faced with the challenges that the Megalopolis has for air quality management and the limited progress of scientific research, it is necessary to direct efforts and allocate resources to carry out field studies of magnitude and objectives similar to the comprehensive campaigns of 2003 and 2006, to update scientific knowledge and promote better air quality management in the region.

2.5. Research on the impacts of air pollution in the Megalopolis

Air pollution has a variety of impacts on human health, including, but not limited to, reduced lung development and function, respiratory infections, and aggravated asthma in children, while ischemic heart disease and stroke are the most common causes of premature death in adults. There is emerging evidence of other effects such as diabetes and neurodegenerative conditions. The evidence base for the harm caused by air pollution on public health has been growing rapidly and points to significant harm caused by even low levels of many air pollutants. This has led to ever-increasingly risk estimates associated with air pollution in the Global Burden of Disease, the World Health Organization's publication of more stringent Air Quality Guidelines in 2021, and updated of the NOM for air quality in Mexico. This becomes even more relevant in the Megalopolis region because it presents significant air pollution problems, which are reflected in frequent non-compliance with regulations, health impacts, direct and indirect economic costs, and damage to ecosystems.

Since the 1980s in Mexico, specialized epidemiological and toxicological studies have been conducted to improve knowledge about the impacts of air pollutants on health, and the key results have been incorporated into policies and programs for air quality control. For example, studies on the harmful effects of lead were important in changing the official standards in which lead was removed from fuels. Other studies include the relationship between air pollutants and asthma, mortality rates, cardiovascular effects, lung development in children, metabolic diseases, cancer, and, more recently, the relationship between pollution levels and the health impacts of COVID-19. In addition to health impacts of criteria pollutants, exposure studies on ultrafine particles and unregulated air pollutants, such as polycyclic aromatic hydrocarbons (PAHs), have been conducted in Mexico. Some of these studies are described in Chapters 4 and 5.

In addition to the impacts on human health, atmospheric pollutants can damage crops, reducing their yield and increasing the risk to food security. They can also affect forests and ecosystems by reducing the quality and quantity of the environmental services they provide to society. Most studies in Mexico have focused on understanding the impacts of air pollutants on human health; however, there are still information gaps about the impacts on crops, forests, ecosystems, cultural heritage, and public and private infrastructure.

2.6. Air quality management programs in the Megalopolis

In Mexico, the Federal government has pursued an air quality management approach through the air quality improvement programs (ProAire, *Programa Para Mejorar la Calidad del Aire)*, which responds to the need of each of the thirty-two states that make up the country to have a preventive and/or corrective instrument in terms of air quality and health protection, as well as to comply with the applicable legal framework. At the scale of the Megalopolis, in August 2017 the Federal Management Program to Improve the Air Quality of the Megalopolis 2017–2030 (*ProAire de la Megalopólis* 2017-2030) was published, with the main objective of improving air quality in the region focusing on sources under federal jurisdiction..

In the 1990s, due to the severe air pollution problem in the Federal District (now Mexico City) and the fact that its administration was part of the federal government, the initial activities of air quality management focused on it and its metropolitan area. The first air quality management program in the MCMA, PICCA (*Programa Integral contra la Contaminación del Aire*), was developed and implemented in 1990, this was followed by ProAire 1995–2000, ProAire 2002–2010, and ProAire 2011–2020. The most recent ProAire 2021-2030 for the MCMA was published in December 2021, which includes policy measures and actions aimed at preventing, controlling, and reducing emissions from priority sources, while addressing cross-cutting issues to strengthen air quality management, such as risk communication processes, citizen participation, institutional arrangements, monitoring, metropolitan coordination, and scientific research.

As in many large urban centers around the world, transportation continues to be a major source of air pollution in the MCMA and the Megalopolis region. Most of the air quality improvement programs aim to reduce transportation-related emissions through circulation restriction, technological changes, electric mobility plans (electric vehicles such as cars, vans, cargo vans, buses, and motorcycles), promotion of sustainable mobility (walking, biking, using public and personnel transport), and teleworking.

As the specific measures to reduce exhaust emissions have been successful, those related to the control of emissions from non-exhaust systems (use and wear of tires, brakes, engines, evaporation of gasolines and coolant liquids, etc.) have become more relevant and are important sources of pollution. Electric vehicles are an alternative to drastically reduce pollution in the short term; however,. there are concerns about the production and disposal of batteries. In the production of electrical energy, it will be necessary to exploit renewable sources to reduce emissions into the atmosphere from fossil fuel-based power plants. The use and final disposal of electric vehicle batteries must be regulated to avoid pollution that could be caused by improper handling.

To encourage the use of low emission vehicles, CAMe announced in 2019 some changes to the “No Driving Day” (HNC, *Hoy No Circula*) program that are applied in the MCMA. All electric and hybrid vehicles are exempt from driving restrictions. In the update of the HNC, incentives were considered for vehicles with lower emissions of criteria pollutants and greenhouse gases and compounds.

To protect the public from exposure to harmful pollutants, in the MCMA, the Atmospheric Environmental Contingency Program, PCAA (*Programa de Contingencias Ambientales Atmosféricas*), in operation since 1986, was replaced by the Program to Prevent and Respond to Atmospheric Environmental Contingencies, PPRECAA (*Programa para Prevenir y Responder a Contingencias Ambientales Atmosféricas*) in 2019, which updates the activation threshold levels for O_3 and PM_{10}, in addition to incorporating criteria for $PM_{2.5}$ and combined contingencies for O_3 and PM_{10} or $PM_{2.5}$. In the rest of the entities, there are also PCAAs, but with some differences with respect to the PPRECAA. CAMe is currently making efforts towards the harmonization of these programs.

3. CHALLENGES, LESSONS LEARNED, AND RECOMMENDATIONS

The following summarizes some of the main challenges, lessons learned, knowledge gaps, and research needs regarding current state of air quality monitoring, construction of emission inventories, development of air quality forecast models, research in atmospheric science and public health in the MCMA and the other regions of the Megalopolis, as well as some public policy options to improve air quality and protect the population from the effects of pollution.

3.1. Air quality monitoring in the megalopolis

Challenges of air quality monitoring

The Mexico City Monitoring System (SIMAT) has maintained a constant quality in its work over the last two decades, which allows for reliable air pollution trends to objectively assess the evolution of the impacts of urban development and the results of management. Despite the increasing importance of SIMAT for environmental management and the contribution to the protection and improvement of the health of the large population of the MCMA, the human resources and annual budget allocated for monitoring are limited and could affect compliance with the basic needs of operation and maintenance. Therefore, it is necessary to explore cooperation mechanisms to increase technical and economic participation among the entities that made up the MCMA.

Air quality monitoring in the Megalopolis has focused mainly on urban centers. Therefore, there is little information on the spatial representativeness of the networks/stations based on the monitoring objectives and the air quality situation in the peripheral urban settlements, rural areas, and natural areas. Despite the fact that in most of the entities that make up the Megalopolis, monitoring has been carried out for more than a decade, the monitoring systems present different levels of maturity, which is directly reflected in their operation and performance, with a significant disparity in the data quality. Most networks do not have monitoring and data quality objectives, nor adequate plans or protocols for quality control and assurance. The spatial representativeness of the networks/stations based on the monitoring objectives and the metrics for quality assessment during monitoring and data validation are unknown. There is little information on the level of certainty of the data and the impact of these limitations on decision-making and on the achievement of management goals.

Although this document does not intend to carry out an evaluation of the performance of the monitoring networks, some aspects emerged from the review of recent public data that require the attention of the environmental authorities, which are mentioned below:

- The Megalopolis region is underrepresented by atmospheric monitoring. There are important gaps in the spatial distribution of air pollutants, both at the urban and regional scales. There is scant evidence on the air quality situation in areas of ecological value, agricultural extensions (important for food security), and small towns.
- There are challenges in reducing the disparity in data quality between the different monitoring systems. In some cases, the data have uncertainties that are difficult to quantify, severely limiting their use for air quality management and for public information.
- Some air quality monitoring systems do not perform adequate validation before publishing their data in their local repositories or in the National Air Quality Information System (SINAICA, *Sistema Nacional de Información de Calidad del Aire*). Deficient data should be identified and invalidated during the monitoring process, prior to publication.. On the other hand, the approval and publication of these data in the SINAICA repository gives a false sense of confidence for monitoring networks that are producing deficient data.
- The lack of economic, technical, or human resources is a constant in all monitoring systems. This is a very important limitation that must be addressed, since air quality management depends on them and they are also a tool for public health protection.
- Most monitoring systems do not have an adequate data quality management program.
- All monitoring systems report pollutant concentrations that exceed the limit values of the Official Mexican Standards, mainly for O_3, PM_{10} and $PM_{2.5}$. The highest O_3 concentrations are observed from March to May, while those of suspended particles are between November and May, during the dry season. Between June and October, during the rainy season, pollution levels decrease throughout the region. It is important to note that two of the most polluted days in all states usually occur at Christmas and New Year’s Day due to the burning of fireworks and bonfires.
- Acid rain continues to be a problem in the territory of Mexico City; however, environmental management has been neglected and the situation in the other entities of the Megalopolis is unknown.

Recommendations to improve air quality monitoring in the Megalopolis

The recommendations presented below are intended to invite local and federal authorities to carry out a diagnosis of how the monitoring networks are operating and the quality of the data they are collecting. This will allow them to take the necessary actions to improve the performance of atmospheric monitoring in the Megalopolis region. The list of recommendations presented here is not exhaustive, but it does cover the major deficiencies found in air quality monitoring networks during the preparation of this document.

- ***Implement system audits and technical evaluations.*** Carry out system audits and technical evaluations of monitoring networks in order to identify their capacities and deficiencies in each stage of the monitoring process. These evaluations must be carried out with specialized personnel, preferably by independent third parties outside the monitoring programs. Based on the results, establish realistic goals and work plans to guarantee the continuous and permanent improvement of the proper operation in the short term.
- ***Implement quality control plans.*** Design and establish standardized plans for assurance and control in the different stages of monitoring, with the purpose of advancing towards the harmonization of the quality of the data generated in the region. Establish appropriate quality metrics to assess the quality of the work carried out by the monitoring networks.
- ***Define validation objectives and metrics.*** Define objectives, criteria and metrics for data validation; prepare protocols or procedures for data validation both on the side of the data producer and SINAICA. Validation must be traceable and auditable.
- ***Evaluate spatial representativeness.*** Develop protocols for the evaluation of spatial representativeness and, based on them, carry out a review of the location and pollutants measured in all the monitoring stations in the region. In those where their location compromises the monitoring objectives, carry out the necessary actions for their relocation, using harmonized protocols based on scientific evidence (for example, regional air quality models).
- ***Incorporate long-term financing mechanisms.*** Guarantee the sustainability of monitoring networks with appropriate budgets that include state, municipal and federal participation. Explore financing mechanisms, for example., trust funds, as well as the participation of private resources, such as foundations, that allow the operation of monitoring networks in the long term.
- ***Establish monitoring in non-urban areas.*** Consider establishing monitoring stations to cover spatial gaps, generate data on pollution levels in rural areas and areas of ecological interest. Incorporate environmental justice criteria in the selection of monitoring sites.
- ***Retrospective validation of data.*** Based on the monitoring objectives, carry out a retrospective analysis of the data generated by the different monitoring systems and identify data of questionable quality with appropriate flags.
- ***Strengthen the monitoring infrastructure.*** Through the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis (*Programa de Reforzamiento de las Capacidades de Monitoreo de la Calidad del Aire en la Megalópolis*), 150 million pesos were allocated to strengthen the monitoring infrastructure and prop up a Megalopolitan Air

Quality Monitoring System. As of December 2022, the program presented a physical and financial progress of 94%. Although there is confirmation of the purchase of equipment and infrastructure, the presentation of clear and objective evidence of the benefits achieved in monitoring. the quality of the data, and the dissemination of information by the funded entities is still pending.

- ***Expand technical capabilities.*** Develop continuous training programs to increase the technical capabilities of the personnel of the atmospheric monitoring networks.
- ***Incorporate satellite measurements.*** The increasing availability of satellite data and a new generation of satellite air quality monitoring may provide scientists and policy makers with additional information about the concentrations of criteria pollutants, which may be valuable for regions of the Megalopolis outside the spatial coverage of monitoring networks. However, satellite data will not replace surface monitoring, rather, they are complementary. It is necessary to establish new stations and continue monitoring ambient air quality routinely with regulatory grade instruments in such areas.
- ***Incorporate calibrated and validated low-cost monitors.*** Recent developments in sensor technology have improved the performance of low-cost monitors and allow them to be used under particular conditions to complement current monitoring systems and create new applications to better report the state of air quality. However, this will only be possible if a robust device calibration and data validation scheme is implemented to reduce uncertainties in their measurements.
- ***Public dissemination of information.*** It is important to maintain the permanent dissemination of the monitoring results to the population through the mass media, websites, applications and social networks.

3.2. Atmospheric pollutant emissions in the Megalopolis

Challenges and recommendations to improve the estimation of emissions

- ***Incorporation of quality control methods during the construction of emissions inventories***. It is important that the working groups responsible for the development of emissions inventories relevant to the Megalopolis implement the quality control methodologies that are available for the preparation of emissions inventories. The systematic application of quality control during the preparation of an inventory is crucial to obtain coherence, integrity, comparability, representativeness, and transparency of the information obtained.

  The application of quality controls allows identifying the main areas with uncertainty in the inventory, as well as the existing challenges to improve the estimates in each successive version. Quality control must be incorporated with statistically robust techniques parallel to the preparation of the inventory and not after. One of the main challenges to systematically incorporate quality control processes is to institutionalize support to the working groups in terms of allocating the necessary financial, infrastructure, and training resources.

- ***Independent evaluation of inventories*.** The INEM, INEGYCEI, and the IE-ZMVM generally use a combination of methods for estimating emissions including: (1) direct sampling of sources (mainly for industrial sources); (2) indirect estimates using a combination of techniques of mass balance and models, for example, MOVES-Mexico, *Modelo Mexicano de Biogás,* the Non-Road model for off-road sources, and the Emissions and Dispersion Modeling System (EDMS), etc.; (3) extrapolation techniques for the combination of emission factors with activity data; and (4) IPCC guidelines for estimating GHG emissions.

  The joint application of the various methods represents a significant effort to obtain, process, and analyze the information necessary to prepare the emission inventories. However, it is necessary to incorporate techniques to assess uncertainty and independent review. Estimated emissions must be based on the verification and analysis regardless of the source of information used. The first challenge to be solved is the systematic promotion of the work and continuous collaboration with federal, state, and local institutions and agencies that generate and process the activity data, to ensure consistency between reported data, the approximations used and the data obtained under real operating conditions.

  The experience of the field measurement campaigns in the MCMA in 2002, 2003, and 2006 showed that the integrated information from field studies, modeling activities, monitoring networks, targeted consultations, and guided tours, is an important tool that can be used successfully for evaluation and analysis of emissions estimated in local inventories. Some valuable tools for independent assessment of emissions use indirect methods such as independent modeling of emissions in combination with measurement campaigns, as well as long-term studies with the joint application of various techniques, including remote sensing for mobile and industrial sources, inverse modeling techniques, satellite information processing, eddy covariance flux towers for area sources, sampling in tunnels and with portable systems for vehicular emissions, etc.

- ***Update of emission factors and activity data*.** Due to the continuous changes in technology, regulatory fuel requirements, and changes in the processes, it is necessary to periodically update both emission factors and activity data. It is essential that the decision makers and the environmental authorities of the Megalopolis promote support for the preparation of field studies and surveys to update the information used in the inventories.

  There are key emission sources that need to be prioritized for periodic updating of emission factors and activity data, examples of these sources include gasoline vehicles, off-road vehicles, motorcycles, heavy-duty diesel vehicles, and those used in passenger and freight transportation. Some key sources with high uncertainty in their estimates and which need to be continually reviewed include emissions of resuspended dust on the roads, VOCs from paints, handling of solvents, disinfectants, cleaners, waterproofing and infectious waste, as well as emissions from cooking in the informal sector and from services.

- ***Coordination between environmental authorities and working groups that develop emission inventories*.** It has been observed that each entity that makes up the Megalopolis is both an emitter and a receiver of pollutants, therefore it is necessary to strengthen the metropolitan coordination between the different entities to improve the estimates of emissions at the regional level. In addition, it is essential to improve the coordination between the working groups that prepare emissions inventories, which will allow the generation, processing, and analysis of the information to be efficient and transparent. This will contribute to improving air quality management and reducing pollution levels in the Megalopolis. It is important to understand the regional emission and transport of pollutants to coordinate control measures within the Megalopolis. Many of the public policies will only be able to maximize their benefit if there is coordination between the government agencies of the different entities.

- ***Increase and expand technical capabilities***. As part of the implementation of a process to improve coordination between environmental authorities, it is also important to increase and expand the technical capacities for the preparation of inventories by the working groups of the different entities of the Megalopolis at the federal, state, and municipal levels. Better coordination and technical capacity are required to generate (in successive versions) a regional emissions inventory for the Megalopolis that is comprehensive, robust, accurate, reliable, and that serves as support for modeling, forecasting, and the design of programs to improve air quality. It is necessary that the reports of the emissions inventories, the calculation methodology and the handling of uncertainties be publicly accessible.

- ***Improve the estimation of mobile sources.*** In the case of vehicle emissions, most of the inventories currently developed in Mexico use the MOVES-Mexico model, which is an adaptation of the MOVES (Motor Vehicle Emissions Simulator) model of the United States Environmental Protection Agency. United States (US EPA). The MOVES-Mexico model allows estimating emissions by adjusting the calculations with local databases such as data from remote sensing monitoring campaigns, data from vehicle verification programs, emissions tests on new vehicles and fuel formulation, in addition to the weather condition and local and regional characteristics. However, a major challenge in the adaptation is the adequate representation of actual driving conditions. Therefore, due to the particularities of the traffic that different cities have, the estimates of the emission factors and activity data must be improved.

  The first version of MOVES-Mexico was used in Mexico in 2016, making adjustment to the United States MOVES model 2014a version, for estimating emissions from on-road vehicles. In 2022, the model for Mexico was updated as MOVES-Mexico 2022, adjusting the databases with recent information from remote sensing, vehicle verification programs, fleet, and vehicle activity. The model will be publicly available in the second half of 2023.

  MOVES-Mexico 2022 was based on the United States MOVES 2014b model, rather than MOVES3, which was published by EPA in 2022 and included state of the science on mobile source emissions. However, the modifications of MOVES3 would not apply in Mexico since they include new emission measurements in the United States and also adjustments to emissions from non-road vehicles whose emission factors have not been evaluated for Mexico.

As part of the short-lived climate forcers (SLCF) campaign, coordinated by the MCE2 in Mexico City in 2013, the components of fine particles (BC, organic carbon, and other inorganic components of $PM_{2.5}$) and gases (CO, NO_x, SO_2, VOCs) present in the emissions of various diesel-powered vehicles (buses, freight trucks) encompassing different model years and emission level technologies in Mexico City were obtained under real driving conditions using the chasing technique with the Aerodyne Mobile Laboratory (see Chapter 4, Section 4.5). Comparison of the results with US-EPA MOVES 2014b model showed disagreements for several species, demonstrating the need for using locally-obtained emission factors to reduce the uncertainty in the emissions estimates. It is necessary to consider not only adjusting the MOVES-Mexico model to local conditions, but also updating its base version to improve the estimates.

Also in 2014, emission factors for gases (CO, CO_2, and NO_X) and particulate matter (BC component and total PM) for a variety of non-road diesel vehicles (construction and agricultural equipment) were also obtained using Portable Emissions Measurement Systems (PEMS) technique in high temporal resolution with and without diesel-particle filter (DPF). The results showed that the reductions for BC emission factors were significantly greater (>99%) with installed DPFs. In contrast to on-road vehicles, there is still no regulation for the emissions levels of in-use non-road vehicles. Their relative emissions contributions increase over time as emissions from on-road vehicles continue to be reduced by advanced technologies. There is a strong need to increase the emission factors database for non-road vehicles in the Megalopolis through field studies and to continue studying the benefits of non-road vehicle emission control technology in the Megalopolis.

In addition to emissions from automobile exhaust systems, it is important to characterize evaporative emissions from the fuel system and those from the use and wear of tires, brakes, and other non-exhaust systems, which include toxic metals.

Currently, the project, "Inventory of pollutant emissions from on-road mobile sources for the Megalopolis for 2018 base year and the update of the MOVES Mexico model" (*Inventario de emisiones contaminantes de fuentes móviles carreteras para la Megalópolis con año base 2018 y la actualización del modelo MOVES México)*, is being executed by CAMe and SEMARNAT, financed with resources from the Environmental Trust (FIDAM-1490). This project will support and provide training to the seven entities that make up the CAMe for the development and updating of their emissions inventory.

- ***Improve the estimation of evaporative emissions from fossil fuels***. The control of fuel losses by evaporation during the handling and supply processes must be based on a comprehensive strategy for regulation, optimization, updating and improvement in the different phases of distribution from the refineries, the storage terminals and service stations, as well as in the application of technical methods to measure emissions and assess their efficiency. It is necessary to guarantee the reduction of emissions during storage, transfer and sale through the use of Vapor Recovery Systems (SRV, *Sistemas de Recuperación de Vapores*), whose operation must be continuous and efficient in accordance with NOM-004-ASEA-2017. The NOM-006-ASEA-2017 establishes the specifications, technical criteria, and requirements for industrial safety, operational safety, and environmental protection that must be carried out in land-based storage facilities for oil and petroleum products. The standard indicates that facilities must control gasoline vapors during the loading of tanker trucks with an efficiency equal to or greater than 95%, but it does not establish the test methods, so there is no evidence of their operation or quantification of emissions control. Similarly, NOM-005-ASEA-2016 indicates that service stations must have hermetic devices to control gasoline vapors during the unloading of tanker trucks. However, the standard does not establish the test parameters or methods. Currently, a CAMe project is evaluating the coverage and performance of SRVs at gas stations and will propose modifications to NOM-005-ASEA-2016 and NOM-006-ASEA-2017.

- ***Improve estimates of industrial sources***. In the estimates, the US EPA emission factors are mainly applied, which are not necessarily applicable to the operating and technological conditions of industrial processes in Mexico. Furthermore, when rigorous quality control is not followed, the calculations tend to have errors, and the vast majority of the data recorded in the Annual Operation Certificates (COA, *Cédulas de Operación Anual*) do not have the necessary operational representativeness for emissions inventories. The data is recalculated taking into account the activity data, historical information and other information sources, since the industry reports have multiple errors. Several entities do not have the annual reports of the industry under state jurisdiction or they do not report annually or reliably. There is also large uncertainty regarding fugitive emissions and the operating efficiency of control systems reported by the industry. These limitations underscore the need to reduce uncertainty in estimates from industrial sources.

- ***Improve estimates of area sources.*** Area sources are small but numerous and contribute significantly to PM, CO_2, VOCs, ammonia (NH_3), SO_2 and toxic compounds emitted from various sources, including: storage, distribution and transfer of gasoline and liquefied petroleum gas (LPG), use of commercial and domestic solvents, consumer products, waste management (landfills, open burning, wastewater treatment, untreated wastewater), agricultural activities (crop burning, tillage, fertilizer and pesticide application, cattle feedlots, enteric fermentation, manure management), dust resuspension, etc. Unlike large stationary sources, area sources generally must comply with less stringent emission limits Many of the micro-industries belong to the sector from the informal industry that is not effectively regulated; they are small and too numerous to be inventoried, contributing to one of the largest uncertainties in emissions estimates. For example, area sources contributed to 66% of the VOCs in the MCMA in 2018. There are numerous small manufacturing, painting, mechanical service workshops, among others, which are part of the informal sector that together can have significant contributions from some pollutants such as VOCs. As urban VOC emissions from transportation-related sources have decreased due to technological advances and regulatory measures, volatile chemicals from sources such as personal care and household products, aerosol coatings, paint, the use of solvents and pesticides have grown in importance, highlighting the need for regulatory action to control sources. As described below in specific categories (VOCs, biomass burning, greenhouse gases), it is important to support field measurements to estimate emission factors for area sources, as well as studies to improve the estimation of activity data.

- ***<u>Measurement of emissions of VOCs and toxic organic compounds</u>.*** VOCs are of interest in part because they participate in atmospheric photochemical reactions that contribute to the formation of O_3 and have a role in the formation of secondary organic aerosols. In addition, many individual VOCs are known to be harmful to human health (air toxics).

  The VOC emissions inventory has one of the largest uncertainties in the emission estimates. During 2018, VOCs in the ZMVM were emitted from a variety of sources, including motor vehicles, chemical manufacturing facilities, refineries, factories, commercial and consumer products, and natural (biogenic) sources (mainly isoprene and monoterpenes from trees). About two-thirds of total emissions (66%) are generated by area sources, including commercial and domestic use of solvents, along with LPG (mainly propane and butane) leaks.

  Commercial and domestic use of solvents contributes approximately 32% of total VOC emissions. Within this activity, certain products have a greater contribution, such as personal care products, pesticides and other products for domestic consumption, industrial cleaners, architectural coatings and automotive care products. With this in mind, the creation of standards that limit the content of VOCs in priority products should be encouraged, while promoting the purchase of merchandise with lower content of these substances. Efforts to control VOC emissions must also focus on addressing LPG leaks in homes, businesses, services and industries, which together generate 20% of emissions. Measures are required to reduce leakage, promote responsible consumption of this energy and move towards more environmentally friendly fuels and renewable energy technologies, such as solar heating systems and water heaters.

  <u>Toxic pollutants</u> are compounds that have the capacity to directly produce adverse effects on the health of the population or the environment. Most of these contaminants are VOCs such as toluene and xylenes, although the classification also includes elements such as lead, other heavy metals, phosphorus, and their compounds.

  In the MCMA, toxic organic compounds represent 29% of total VOC emissions, and area sources are the main source of emissions, with a contribution of 69% of total toxics. The main emitting activities are related to the domestic and commercial use of solvents, the management of urban waste and the distribution of gasoline.

  Efforts are currently being made to improve the characterization of unregulated toxic organic compounds in the Megalopolis. An example of this is the use of techniques such as the Thermal Desorption Aerosol - Gas Chromatograph - Mass Spectrometer (TAG-GC-MS) by the ICAyCC-UNAM Laboratory of Chemical Speciation of Atmospheric Organic Aerosols. The objective is to improve the understanding of the origin of compounds such as polycyclic aromatic hydrocarbons (PAH) and their relationship with mobile sources, industrial sources, solvents, household products, paints, waterproofing, garbage, and products for personal use, among others.

  Due to its relevance in atmospheric chemistry and its toxic effects, it is important to maintain and increase support for studies aimed at characterizing the emissions of VOCs and toxic organic compounds. In addition to characterizing the chemical speciation of VOCs, studies should prioritize a better understanding of the spatial and temporal distributions of organic compounds in the Megalopolis..

- ***Emissions from motorcycles***. An important challenge is to regulate the use and improve the estimation of emissions from motorcycles in the Megalopolis. In recent years, the growth in the use of motorcycles in the region has been explosive. Among other factors, it is due to the versatility of this type of units to circulate under conditions of high vehicular congestion (generally ignoring traffic regulations), the lower acquisition price, and the lack of adequate regulation. The importance of regulating the use and maintenance of motorcycles, as well as improving the estimates of their emissions, lies in the fact that they can potentially circulate with highly polluting emitting technologies, negatively impacting air quality. Currently there are no regulations for motorcycle emissions, but SEMARNAT coordinates a working group for the preparation of a NOM project to limit its emissions.

- ***Improve estimates of fires, biomass burning and dust storms***. Biomass burning is one of the largest sources of trace gases and aerosols emitted into the global atmosphere and is the dominant source of BC and primary organic aerosols. Smoke from the fire is also a significant source of greenhouse gases, including CO_2, CH_4, and N_2O. Other pollutants emitted include CO, volatile, semi-volatile, and non-volatile organic compounds, NO_X, NH_3, hydrogen cyanide (HCN), and nitrous acid (HONO). There are many sources and types of fires related to biomass burning emissions; some are natural sources such as uncontrolled and unplanned wildfires, while others such as emissions from burning crop residues, municipal solid waste, burning residential wood for cooking and heating, and biofuel for production of bricks, are the result of human activities. Different approaches have been used to estimate emission factors for biomass burning in Mexico City and the surrounding region, including direct measurements on fires in field experiments, aircraft measurements, and laboratory measurements as part of the MILAGRO and SLCF campaigns. Despite important advances in measurement of emission factors, detection and quantification of biomass burning, there is a need to improve the accuracy of activity estimates, both for open burning and biofuel use.

  The evidence suggests that the exceptional episodes with high concentrations of pollutants in the region are linked to particular meteorological conditions, together with the contribution of large regional emission sources, such as the burning of biomass (agricultural and forestry) and particle emissions from exposed and eroded soil. It is important to promote and support field, monitoring, satellite, and modeling studies to better characterize the emissions from these sources and thereby manage the procedures to be followed by the population and environmental authorities during environmental contingencies.

- ***Improve the estimation of greenhouse gases.*** The IPCC guidelines are generally used for estimating GHG emissions with comparable techniques in all countries, including Mexico.. As part of the SLCF campaign coordinated by MCE2 to better characterize the major emission sources of BC, CH_4, and co-pollutants in Mexico, field studies conducted in Mexico to characterize CH_4 emissions from wastewater treatment plants and enteric fermentation from cattle indicated that the IPCC methodologies represent an inaccurate tool for estimating local greenhouse gases (see Chapter 4, Section 4.5). It is important to determine specific emission factors for each emitting source locally in order to more accurately estimate GHG emission inventories. Based on these best estimates, more effective mitigation policies can be identified and applied.

In addition, the field studies demonstrated the importance of obtaining emission factors of BC and co-pollutants under real operating condition from on-road and off-road vehicles, brick kilns, and cookstoves, to improve the emission estimates, since Mexico was the first country committed to reducing BC as part of its Nationally Determined Contribution (NDC) to the UNFCCC.

- ***Incorporation of satellite data and remote sensing for the evaluation of emissions*.** There are efforts by the academic sector in conjunction with environmental authorities to incorporate the use of satellite information as a tool for evaluating emissions inventories. An example is the use of NO_2 and formaldehyde (HCHO) columns from the TROPOMI instrument of Sentinel-5P to assess changes in emissions in regions of the Megalopolis. Due to their large potential for evaluating emission estimates in inventories, it is important that the use of these techniques be expanded in Mexico. The incorporation of satellite data for the evaluation of emissions should also include the application of techniques that characterize the vertical structure, mixing, ventilation, and dispersion processes of the atmosphere such as ceilometer measurements, radiosondes, Doppler lidars and modeling exercises. The integration of these techniques is necessary to understand and predict the interaction between emissions, meteorology, and pollution levels in the Megalopolis.

3.3. Atmospheric scientific research in the Megalopolis

Sources and processing of atmospheric pollutants

Lessons learned

- The MCMA-2003 and MILAGRO studies suggest that, during the first decade of this century, the atmosphere of the MCMA was highly sensitive to VOCs in the urban core but could be VOC-or NO_X-sensitive in the surrounding region depending on meteorological conditions. Recent study indicates that it is likely there is a substantial spatial difference in the sensitivity of O_3 to VOCs, including important differences in various areas of Mexico City and its periphery.
- The levels of primary pollutant (CO, NO_2, SO_2) in the MCMA are highly sensitive to changes in anthropogenic emissions. This has been demonstrated during the fuel supply problems in January 2019 and in the effects of the suspension of activities and mobility restrictions during the COVID-19 pandemic after March 2020.
- Experience gained from changes in emissions resulting from drastic measures taken by the governments during the COVID-19 pandemic shows that the formation of secondary pollutants such as O_3 was not controlled by reductions in primary pollutants. Furthermore,

this highlights the importance of meteorology and episodic contributions in evaluating air quality when large emission reductions occur. During the pandemic, the activity and distribution patterns of the vehicle fleet, as well as domestic and service activity, were modified, this could have impacts on the concentration and variety of precursors and, consequently, on the chemical reactivity of the atmosphere.

- Non-linear relationships between precursor pollutants and the formation of secondary compounds (including their effects on peak concentrations) need to be further investigated under various meteorological conditions, along with climate change and socio-economic drivers that may affect future air quality in the Megalopolis,
- The effects of changes in the ratio of precursors and variations in the chemical composition of VOC emission profiles (both from fossil fuel combustion and evaporative processes) on the formation of secondary pollutants should be investigated under various meteorological conditions in the Megalopolis.
- The production of secondary aerosols responds to changes in the composition of their precursors and meteorological conditions, therefore their sensitivity to different gaseous compounds forming them under different meteorological contexts should be investigated.

Knowledge gaps

- What meteorological processes control the temporal and spatial distribution of gaseous and particulate pollutants in the atmosphere?
- What are the emerging factors (for example, new emission regulations, changes in technology, social behaviors) that intervene in the formation of pollutants in the Megalopolis and how can they be controlled?
- Has O_3 production changed in the MCMA? In which sectors of the city is O_3 produced in regimes sensitive to VOCs or NO_X? Are there seasonal, weekly, and diurnal transitions between chemical regimes?
- What are the current profiles and spatial distribution of mixtures of VOCs, semi-volatile organic compounds, and persistent organic compounds in the Megalopolis? What are the contributions of these compounds to the formation of O_3 and secondary organic aerosols (SOA)?
- What are the impacts of air pollution on the natural ecosystems of the Megalopolis?
- Based on the experience during the pandemic, how do changes in the vehicle fleet and domestic activity modify the chemical reactivity of the atmosphere?

Impacts of Tula-Tepeji industrial corridor on the air quality of the MCMA and the Megalopolis region

- Why fuel quality has not improved in the Tula-Tepeji corridor?
- Is it possible to establish a monitoring system for emissions from the industrial complex? What are the viable alternatives to reduce emissions from priority sources?

- What is the content of toxic compounds present in the plumes that transport air pollutants from Tula?
- How do emissions contribute to the burden of disease associated with air pollution in and around Tula, as well as in plume trajectories?
- How do emissions from the industrial corridor affect other cities in the region, for example, Toluca, Pachuca, Tulancingo, San Juan del Río?
- Is there any impact of atmospheric acid deposition on agricultural areas and conservation land in the entities of the Megalopolis?
- In addition to the Tula-Tepeji industrial corridor, are there other sources of anthropogenic pollution with regional impact?
- How do the regional contributions of anthropogenic pollutants affect the management objectives in the entities of the Megalopolis?

Regional scientific research

- The information available from monitoring indicates that some cities within the Megalopolis could have pollution levels similar to and even higher than those observed in the MCMA.
- Air quality management programs require solid up-to-date scientific support for the development and evaluation of control strategies to improve regional air quality.
- Scientific studies that allow us to understand the processes of transport and transformation of pollutants are scarce outside the MCMA. It is necessary to advance the study of meteorological phenomena associated with the regional transport of pollutants, the identification of natural and anthropogenic sources with regional impact, the effects on health and ecosystems, the impacts on local management goals and the design of strategies to mitigate regional emissions..
- Information on the effects of pollution on human health outside the MCMA is scarce; it is a priority to know the situation in the other entities of the Megalopolis.
- Air quality monitoring in the region is limited; it is necessary to increase spatial coverage focusing on priority pollutants in the different regions and improve the dissemination of information for health protection purposes, including non-urban areas and areas of interest for the protection of crop and forest resources, modeling or validation of satellite data.
- It is necessary to promote institutional, financial, and technical efforts to reduce disparity in monitoring activities, emissions inventory, modeling, scientific research, and management in the region, under the coordination of CAMe.

Local meteorology and air quality

Lessons learned

- It is necessary to study the characteristics of the planetary (or atmospheric) boundary layer and its effects on air pollution. Meteorological (for example, wind, temperature, humidity) and aerosol profilers have proven to be a robust tool for measuring and investigating the behavior of various variables in the planetary boundary layer with high temporal resolution. The study of the boundary layer properties requires multiple techniques, combining remote sensing with radiosonde observations, where each technique will provide different information on the mixing, ventilation and dispersion processes.

- Open questions remain about the different processes in the boundary layer that control mixing and the surface concentrations of pollutants, as well as boundary layer interaction between neighboring basins, therefore, different synchronous instruments are needed at multiple locations to better understand their temporal and spatial variability.
- The studies presented in Section 4.4.2 of Chapter 4 describe recent knowledge about the mixed layer, its daily and seasonal variability, and the potential uses of the ceilometer to better understand the relationship between the mixed layer and air quality. However, questions regarding how this interaction influences extreme pollution events in the context of climate change remain to be investigated.
- The possible effects of radiation on the formation of O_3 is a relevant aspect for management; it has been observed that with the increase in solar radiation, the production of O_3 also increases.
- The ProAire 2021-2030 considers a reduction in aerosols, however, this could induce an increase in O_3 concentrations due to the increase in solar radiation that reaches the surface. On the other hand, the changing climate could impact the formation processes of secondary pollutants.

Knowledge gaps and research needs

- What is the intensity of the urban warming in the different urban conglomerates in the Megalopolis?
- How does the urban warming affect the micrometeorology of the cities in the Megalopolis?
- What impacts does urban warming have on the regional climate and atmospheric chemistry?
- Should management plans consider the effects of the urban warming on pollutant reduction goals? Should they include actions for their mitigation?
- What are the expected effects of climate change on meteorology and air quality in urban and non-urban regions in the entities that make up the Megalopolis?
- The available evidence indicates with some degree of certainty that the increase in temperature will bring about changes in the chemistry of the atmosphere and in the production of O_3, however, there is large uncertainty in the magnitude. The concept of climate penalty refers to the possible increase in the concentration of O_3 in environments with high levels of its precursors. In this sense, how will the climate penalty affect the reduction goals of the different management plans? Should management plans include climate penalties?

Short-Lived Climate Forces

Black carbon emissions from on-road and off-road diesel vehicles sector

- The results of the field studies highlight the need for using locally-obtained emission factors database in developing countries to reduce the uncertainty in the emissions estimates and to improve the evaluation of the effectiveness of emissions reduction measures.
- Estimating emissions from in-use off-road vehicles for construction and agriculture is challenging because the extent of emission factor datasets available is considerably more limited compared to on-road vehicles.
- Due to their durability, off-road vehicles are often kept in service for several decades and thus their relative emissions contributions increase over time as emissions from on-road vehicles continue to be reduced by technological improvements. Thus, off-road vehicles are potentially large contributors to BC emissions in many parts of the world, highlighting the importance of designing emissions control strategies and a strong need to increase the emission factors databases for off-road vehicles through field studies.

Methane emissions from wastewater treatment plants

- Drainage and treatment plants are important sources of CH_4 and N_2O.
- Adopt treatment systems with low energy consumption as this represents more than 60% of total CH_4 emissions.
- Improve the operation of primary sedimentation (frequent purges).
- An adequate treatment of the sludge must be given, preferably one that considers the production and use of biogas
- The IPCC Tier 1 methodologies (2006 and 2019) represent an inaccurate tool as they underestimate emissions.
- It is important to determine specific emission factors to more accurately estimate GHG emission inventories. Based on this, more effective mitigation policies can be identified and applied.

Methane emissions from livestock enteric fermentation

- It is necessary to continue the studies on CH_4 emissions from enteric fermentation of cattle under different production and feeding systems in Mexico, including other ruminant species such as sheep and goats.
- Strengthen the studies of specific CH_4 emission factors for manure management for Mexico.
- Design mitigation strategies for CH_4 emission by enteric fermentation of cattle applicable on a commercial scale.

- Strengthen the studies of specific N_2O emission factors for Mexico. On this issue, progress has been minimal.
- Perform life cycle analysis of GHG originating in the agricultural sector.

Air quality modeling and forecasting

Improve model development and application

- Use inverse models to complement bottom-up inventories, considering their potential to improve the spatial and temporal resolution of the inventory and to estimate the location and intensity of known and emerging emission sources.
- Allocate resources to reduce uncertainty in inventories, improve profiles and estimates based on measurements, and advance knowledge about the participation of VOCs in the production of aerosols and gaseous pollutants of photochemical origin.
- Obtain data on the characteristics of primary aerosols for different representative environments of the Megalopolis. Obtain meteorological and air quality data outside of the urban areas.
- Explore the best parameterizations of the model for the different regions of interest in the Megalopolis, produce or obtain the data with the appropriate resolutions for the input and evaluation of the model.
- Consider the needs of modeling within research projects and management policies; increase the spatial and temporal resolution of air quality and meteorology measurements. Include modeling needs in the design of monitoring systems.
- Strengthen the modeling capabilities of the region through the construction of an ensemble of models that includes the currently available models (SEDEMA, ICAyCC, Querétaro, etc.), as well as possible future developments.
- Support the efforts of Mexico City to ensure continuous improvement of its forecasting system and guarantee its sustainability.
- Advance towards the assimilation of data from satellite products and other observation networks and profilers, which can be used for both case studies and forecasting. With adequate computing capacity, it is possible to move from limited-area models to global multiscale models and thus study atmospheric pollution in the context of climate change.
- Coordinate inter-institutional efforts in the production, management, and treatment of data to generate useful products for air quality management.
- Apply machine learning algorithms to improve the physical parameterizations of the models, in the estimation of emissions, in the analysis of satellite images and model outputs to adjust the results, and thereby obtain better predictions.

Strengthen human resources

- Train research personnel in the area of data assimilation, use of satellite information, model evaluation, evaluation of the use and application of machine learning in the processes carried out by the models, as well as in the evaluation and post-processing of the products obtained in the modeling.

- It is necessary to increase the number of technical personnel for the maintenance of the supercomputing infrastructure and use of the software.

Develop infrastructure

- Centralization of computer infrastructure and virtualization in the provision of services to provide entities or institutions with computing capabilities, or allocate resources for the acquisition of computer facilities to the entities of the Megalopolis.

Impact of Covid-19 on air quality

Knowledge gaps and research needs

- It is necessary to have accurate emission estimates of NO_x and VOCs in the MCMA and surrounding regions in order to understand the changes in the formation of O_3, $PM_{2.5}$ and other secondary pollutants during the COVID-19 lockdown period.
- The experience during the pandemic showed a new scenario that confirmed the complex interaction between emissions, meteorology and atmospheric chemistry in the urban atmosphere of the MCMA.
- Understand how the chemical composition of VOCs changed during the pandemic.
- There is sufficient evidence that during COVID, the transportation sector was strongly impacted, substantially reducing congestion, but at the same time, increasing the traffic of home delivery vehicles. In general, the industrial sector also decreased its activities, some industries more than others. Food preparation activities at home, in informal sales and the restaurant sector were modified. However, emissions from products for personal use, household products, paints, waterproofing agents, domestic garbage, waste, disinfectants, cleaners, etc. were up. It is necessary to evaluate how the services and commerce sector modified its operations.
- It is necessary to understand how the contribution of domestic emissions (for example, cleaning products, food preparation, burning and leaks of LPG and natural gas, etc.) and from sources other than automobiles and industry (for example, agricultural and forest fires, biogenic emissions, evaporative emissions from other sources, etc.) contribute to air pollution and influence the production of O_3 and secondary aerosols.
- Based on what was observed during the COVID-19 restrictions in the MCMA, the results suggest that vehicle and industrial emission restrictions caused the concentrations of primary pollutants to decrease in ambient air, however, no reduction in O_3 concentrations was observed. Why? How would this affect the objectives of air quality management and the actions that are applied during environmental contingencies?
- Given the observed reductions in $PM_{2.5}$, it is necessary to understand how the reductions in precursor emissions modified the chemistry of the secondary formation of aerosols.
- Regional transport of air pollutants during lockdown period:

    - How did the emission sources from nearby states contribute to air pollution levels in the MCMA?
    - How did the emissions from the MCMA contribute to pollution levels in nearby states?
- It is necessary to have a comprehensive characterization of the atmospheric reactivity, radical budget, and secondary pollutant formation during the lockdown period through modeling studies to understand the air quality during the lockdown period:
- The availability of comprehensive VOC speciation during the COVID-19 lockdown will allow us to evaluate changes in OH-VOC reactivity.
- It is necessary to have a thorough characterization of the local and regional meteorology during the lockdown period to evaluate any potential ventilation enhancement (that is, windy conditions) or favorable condition for photochemistry (that is, more intense solar radiation).
    - What were the meteorological conditions that contributed to high $PM_{2.5}$ and O_3 production/accumulation during high pollution days?
    - What regional and local wind patterns helped to disperse the pollutants during the lockdown?

3.4. Public health studies and air pollution in the Megalopolis

Lessons learned

- ***Incorporation of results from health studies in air pollution control programs***. The results of current studies show evidence of correlations between various types of morbidity and concentrations of air pollutants, mainly for $PM_{2.5}$. Research on health impacts includes effects at the cellular and deoxyribonucleic acid (DNA) levels, chronic lung diseases, different types of cancer, metabolic diseases, neurological effects, concentration-response functions, and the statistical value of life. There is a wide range of studies that provide evidence of the health impacts of air pollutants. However, it is important that these results can be incorporated as support for the design of regulations and programs to reduce air pollution. For this, the scientific community in Mexico must address the issue of representativeness and robustness of the results, so that they can contribute to the establishment of a scientific basis for the design of air quality control strategies. Furthermore, mechanisms must be created to reduce the gaps for efficient integration of the results of health studies in the design of public policies, including activities for prevention, and the reduction of exposure to contaminants that are harmful to health.
- ***Disclosure of information to reduce exposure.*** Another substantial advance has been the real-time disclosure of air quality conditions and their possible impacts on the health of the population of the Megalopolis, based on information from the available atmospheric monitoring networks. The continuous dissemination of information through applications, public reports, news media and social networks helps the population to make informed decisions to carry out their activities in indoor and outdoor spaces that reduce exposure to air pollutants, thereby improving public health and quality of life. These actions have been

essential before, during and after the declaration of environmental contingencies for O_3 and for PM under the environmental contingency programs to alert and inform the population. Information dissemination activities are part of the actions listed in the ProAire for the Megalopolis.

- ***Epidemiological evidence indicates that there is no safe exposure threshold for particulate matter and gaseous pollutants.*** According to the results presented, there is evidence that suggests that the health effects of air pollution are not related to specific limits. The mixture of air pollutants in the different urban areas of the Megalopolis can be complex, their chemical characterization and the possible effects on health are important challenges. This suggests that exposure to concentrations of particulate matter, even below the WHO air quality guidelines, can be dangerous to the health of the population.

Key science questions

- ***Representativeness of morbidity studies***. A key question refers to the need to better understand the representativeness of the results obtained in morbidity studies, such as metabolic diseases, diabetes, and effects on neurological development, among others. It is important to know if the results obtained in the morbidity studies are robust enough to support the development of new initiatives for public policies and new regulations.
- ***The integration of the results of health studies in the design of public policies***. An issue that must be addressed by the scientific community and decision makers is the establishment of mechanisms to integrate the results of health studies into the public agenda. Beyond the scientific establishment of the relationships between effects on morbidity and exposure to air pollutants, it is vital that the information generated assist in the development of air quality improvement strategies.
- ***Health studies for exposure to other pollutants***. Traditionally, health studies have focused on criteria pollutants such as O_3 and particulate matter. However, the population in urban areas is typically exposed to complex mixtures of gases and particles. Thus, there is a need to expand studies of the health effects of exposure to chemical mixtures of VOCs, PAHs, toxic pollutants, metals, nanoparticles, and the complex combinations of compounds in particulate matter. These studies are necessary not only for studies of mortality but also of morbidity.
- ***Exposure studies***. It is necessary to increase and improve our understanding of the characteristics of exposure to air pollutants. This also includes improving the mechanisms to generate the information necessary for exposure studies at the local and regional level. It is important to determine if the results of those studies can be used to improve our understanding of exposure to air pollutants.
- ***Integration of other methodologies***. Improving exposure assessments also implies reinforcing collaboration between the agencies that generate the information, as well as integrating other data generation methodologies such as satellite information, personal monitoring, emissions inventories, and air quality modeling. The integration of these methodologies would make it possible to substantially improve the availability of the databases necessary to understand exposure to air pollutants.

Scientific challenges and research needs

- ***Toxicological profiles***. The results of the toxicological studies show evidence of biological causes and mechanisms that can explain acute, chronic, and trans-generational health impacts. There is, however, the challenge of determining the toxicological profiles of the organic content of particulate matter in different parts of the Megalopolis. It is important to know the regional differences in toxicological profiles to correlate them with specific health impacts for population groups in the Megalopolis.
- ***Impacts due to mixtures of air pollutants and pathogens***. The study of the health impacts of mixing or combining air pollutants with pathogens (e.g., viruses) is still an important challenge that must be addressed by the scientific community. This also includes the need to develop the necessary toxicological methods to use for addressing the problem. The complexity of this challenge increases to the extent that the variability of the spatial distributions of pathogenic microorganisms and the concentrations of atmospheric pollutants is great within the Megalopolis.
- ***Interaction between climate change, air quality and health***. There is a complex interaction at multiple scales between climate change and air quality. However, the connection between local air pollution sources and the emissions that drive climate change is very clear. In addition to adverse effects of anthropogenic pollutants on human health, naturally occurring air pollutants such as pollen, biogenic volatile organic compounds, smoke from wildfires and windblown dust may be influenced by climate change and become an increasing health risk. Climate change could also induce changes in the behavior of the population, for example, the time that individuals remain indoors, as well as modify the availability and distribution of allergens derived from plants and fungi, this will have effects on asthma and allergic rhinitis in children and adults, therefore, policy adjustments and lifestyle changes will need to be addressed to mitigate these deleterious effects.

  When estimating future health impact, in addition to uncertainty in O_3 and PM concentrations, there are uncertainties in risk estimates, such as the modification of the effect by temperature on the relationships between pollutants and the human response, altering potential future adaptation resulting from these changes and a potential new risk associated with the exposure. It is necessary to begin evaluating the implications of climate change on human health and orient policies towards the mitigation of climate change and air pollution, thus enhancing the health benefits and optimizing resources and costs.
- ***Health monitoring system***. An interesting proposal is to design and implement a health monitoring system in conjunction with existing environmental monitoring networks in the megalopolis. The integration of the systems could substantially help the early identification of actions to mitigate exposure to air pollutants, including extraordinary events such as those presented during the COVID-19 pandemic. Furthermore, the proposed integration may help improve the evaluation of the effectiveness of air quality control programs.
- ***Chemical composition of the particulate material and emerging toxins***. The associations between the health impacts and the toxicity of the different chemical speciation in the

particulate matter should continue and increase, especially for the components of PAHs, metals, and black and organic carbon. This will allow us to understand how chemical aggregation and aerosol formation determine the molecular activation of pathophysiological processes of acute and chronic diseases. It is also necessary to carry out studies of emerging toxic particles such as ultrafine particles, microplastic particles and those that do not derive from combustion such as brake and tire wear, identifying their emission sources and toxic potential.

- ***Methods of health studies***. To aid in the development of policies to improve air quality, it is necessary to integrate the results of different methods of epidemiological studies such as ecological, case series, cross-sectional studies, case controls, cohort studies, and interventions. For health studies, *in vitro* and *in vivo* models of exposure to toxicants, high-throughput molecular techniques, and physiological function parameters of chronic diseases must also be integrated. It is necessary to advance in the study of the synergistic effects of the urban mix, as well as the effects of emerging pollutants. Exposure models used in epidemiological studies can benefit from the use of data obtained from satellite platforms and low-cost technologies, as well as from the output of numerical model ensembles.

Knowledge gaps:

- In the Mexican context, is there new scientific information on the health effects related to air pollution? What has been the recent information on air pollution and health?
- Is there evidence of chronic and acute effects aggravated by exposure to poor air quality?
- What are the social and economic costs associated with air pollution?
- What have been the advances to better estimate the health effects of air quality quantitatively?
- Is there a contribution from outdoor ambient air pollution to indoor exposure?
- What are the thresholds for exposure to particulate and gaseous pollutants? What would be the challenges to achieve them?
- Is it necessary to include any other pollutant or pollutants (for example, ultrafine particles, PAHs) within the ambient air quality regulations?
- How will climate change modify impacts on health?

3.5. Air quality management in the Megalopolis

Knowledge gaps

- How to promote the development of scientific knowledge and promote the creation of research centers outside of Mexico City?
- How does the federal government promote scientific work and capacity development in the entities of the Megalopolis?

- What additional data is needed to design and evaluate the ProAires measures of the entities of the Megalopolis?
- What are the main research needs in each one of the urban centers in the Megalopolis?
- Available evidence suggests that the chemistry and physics of the MCMA’s atmosphere are changing. How can the government lead a new measurement comprehensive campaign for the Megalopolis?
- What are the lessons learned for environmental management from the restrictions during the COVID-19 pandemic?

Role of CAMe in coordinating regional air quality management

The Megalopolis Environmental Commission (CAMe) was created in 2013 as a coordination body for the planning and execution of policies, programs, projects and actions related to environmental protection, preservation and restoration of ecological balance, in the region that makes up the Megalopolis of central Mexico.

The CAMe is made up of seven federative entities: Mexico City and the states of Hidalgo, Mexico, Morelos, Querétaro, Puebla and Tlaxcala, and also by four federal government ministries: the Ministry of the Environment and Natural Resources (SEMARNAT), the Agrarian, Territorial and Urban Development (SEDATU, *Desarrollo Agrario, Territorial y Urbano*), Infrastructure, Communications and Transportation (*SICT, Infraestructura, Comunicaciones y Transportes*) and HEALTH (SALUD). It has a Governing Body, which is made up of the Heads of the federal Secretariats, the Governors of the states and the Head of Government. It also has a Scientific Advisory Committee, which is composed of fifteen scientists, academics and experts in environmental matters who have the power to advise and offer their opinions and recommendations on the Commission's priority actions.

For its operation and functioning, the CAMe has an Executive Coordination, which convenes the sessions of the Governing Body, proposes actions and follows up on the agreements. The Executive Coordinator articulates the actions of eight Working Groups, made up of the technical staff of the entities and institutions participating in the CAMe.

The CAMe has Trust 1490 to support the Environmental Programs, Projects and Actions of the Megalopolis (FIDAM 1490). It receives annual contributions of $5.00 pesos for each vehicle verification carried out in the verification centers of the CAMe entities. FIDAM 1490 can also receive contributions from other sources such as donations, remnants of budget savings from its members, among others.

The CAMe could be strengthened with actions such as the following:

- Include the Ministry of Energy (SENER, *Secretaría de Energía*) and the Ministry of Finance and Public Credit (HACIENDA, *Secretaría de Hacienda y Crédito Público*) of the federal government as members of the Commission, to reinforce the implementation of high-impact regional environmental policies, programs and actions.

- Create an Advisory Council made up of representatives of environmental civil society organizations, and business and service chambers and associations from the environmental sector, where they can give their opinion and follow up on issues of common interest, as well as promote constructive dialogue between environmental authorities. and civil society in general.
- Encourage contributions and donations to FIDAM 1490 from other sources, such as the mandatory vehicular verification of emissions from federal license plate vehicles carried out by the SICT, contributions from the industries with the highest polluting emissions, and strengthening the commitment of the contributions derived from the state vehicle verification.
- Advance in other priority environmental issues in which the CAMe can contribute to harmonizing programs and actions, for example, in the simultaneous and harmonized attention to air quality and climate change, circular economy, water quality issues, waste, and mobility and transportation, as well as conservation of Protected Natural Areas, among others.
- Initially, make it a priority to support the promotion of the measures established in the ProAires of the entities to reduce emissions of pollutants in the region's atmospheric basins.
- Drive evidence-based evaluation of the effectiveness of programs and projects in budget decisions and public policies, including the creation of performance requirements in grants and contracts to ensure that programs are executed and meet their objectives effectively.

Air quality monitoring

Although the MCMA has a well-developed air quality monitoring network that covers a large part of the urban area, the spatial coverage of air quality monitoring in the growing metropolitan area of Mexico City and the rest of the Megalopolis is limited. At the Megalopolis level, monitoring is restricted to urban centers. In addition, there is a significant disparity in the quality of the data.

The CAMe has the opportunity to contribute with its management leadership to improve the monitoring conditions of air quality in the Megalopolis. Section 3.1 above lists a series of valuable recommendations that must be managed by CAMe and environmental authorities to improve the quantity, coverage, and quality of data from monitoring networks, highlighting:

- Develop strategic capacities of the Regional Monitoring Network, including different types of sites (urban, peri-urban, rural).
- Provide financial support to improve the infrastructure and technical capabilities of the air quality monitoring network in the Megalopolis, including training in the analysis and validation of satellite data.

Emissions inventories

Emission inventories are an essential air quality management tool for evaluating the progress of emission control strategies and planning future actions. A detailed description of the challenges and recommendations for improving emissions inventories is presented in Chapter 3.

The MCMA emissions inventory is well developed and is used to inform emission reduction strategies. In Section 3.2 above, the challenges and opportunities that exist to improve emission inventories in the Megalopolis were described and that they can be truly useful in air quality management. CAMe can make a decisive contribution to the implementation of the recommendations listed in Section 3.2 by leading the air quality management process in the Megalopolis. Areas of opportunity that can be highlighted include:

- Verify inventory objectives and their alignment with management needs.
- Improve spatial coverage and resolution.
- Review emission profiles and chemical speciation.
- Increase the temporal resolution.
- Publish the information of the calculations and uncertainties.

In all cases it is necessary to include or improve the information on the area sources related to the use of solvents in the residential, commercial and service sectors. Specific studies are required to obtain or improve emission factors and activity data, as well as temporal distributions and chemical speciation.

Air quality modeling and forecasting

The Mexico City government has implemented an air quality forecast system to alert the public of high pollution of O_3 and PM event 24 hours in advance, and in evaluating emission reduction policies for air quality improvement and other co-benefits. Substantial challenges remain in the implementation of the air quality forecast system in the rest of the Megalopolis due to a lack of data and research to support modeling and forecasting efforts, as well as limited qualified technical personnel.

There are efforts by academic institutions to forecast air quality. The ICAyCC-UNAM has a 72-hour forecast model based on WRF-CHEM for CO, NO_X, O_3, PM_{10} and SO_2 with a spatial coverage that includes Mexico City and neighboring entities, the graphic outputs are available for online consultation. There are other modeling and forecasting efforts in academia and other entities, but the information is not public.

CAMe could provide the financial resources and be a catalyst to develop a system for air quality modeling and forecasting in the entities of the Megalopolis, including collaboration with national and international experts to provide training in air quality modeling and forecasting.

Transport and mobility: Integrated transportation-land use-air quality management

The uncontrolled urban expansion and the increased motorization in the Megalopolis are major sources of air pollution and congestion. Creating a transport system in proper balance with the environment requires a transversal strategy that integrates the transport sector, changes in land use, air quality management, and that involves the different responsible organizations (environment, transport, urban development, and public works) and with public participation. The goal would be less reliance on individual vehicles through the provision of better public transport and measures that allow for more journeys to be taken on foot or by bicycle. Some of the actions in which the CAMe should take the lead for its implementation include:

- Promote the infrastructure for active or non-motorized mobility.
- Develop public policies for the optimal location of infrastructure and equipment (Compact Cities with mixed land uses).
- Development of inter- and intra-urban mass transport systems (cargo and passengers).
- Orient the urban development of the Megalopolis towards the containment of its expansion (Densification of the Territory).
- More frequent origin-destination studies for infrastructure planning and to improve operations.
- Promote sustainable mobility (telework, high-capacity public transport, walking and cycling).
- Establish incentives for the introduction of low-emission vehicles, such as electric and hybrid cars, as well as electric motorcycles.
- Consider limiting the use of private vehicle in heavily trafficked areas.

Atmospheric science

Current observations in the MCMA and other entities of the Megalopolis indicate that atmospheric concentrations of pollutants such as O_3 and $PM_{2.5}$ have not decreased to the acceptable limit and show increases in recent years, suggesting the need to update the state of scientific knowledge of the processes that control the formation, transport, and fate of these pollutants. A solid understanding on the changes of the meteorology, emissions and processes that control O_3 formation and other secondary particles in the MCMA and the Megalopolis region is vital in the design of new policy actions. Section 3.3 above describes the challenges and opportunities that exist to improve our knowledge of atmospheric processes in the Megalopolis. Some of the research needs that the CAMe should promote for the development of air quality management strategies are described below:

- ***Extensive atmospheric measurements and modeling studies*** are needed to define optimal emission control strategies for the particular entity in the Megalopolis, considering the local instituional, technical, economic, social, and political circumstances.
  - The application and validation of air quality models requires spatially and temporarily resolved emissions data as well as knowledge of the meteorology and solar radiation. In addition to commonly measured O_3, nitric oxide (NO), NO_2, CO, and PM mass, individual VOCs and PM chemical composition measurements are needed. This detailed information will require special studies to better understand the causes of such emissions and to assess progress in their reduction.
  - Policy makers should use this information to balance the economic and social benefits of health improvements against the costs of emission control.

- ***Climate change impacts on air quality and health***. Climate change can impact air quality and, conversely, air quality can impact climate change. Emissions of greenhouse gases (for example, CO_2, N_2O) and short-lived climate forcers (CH_4, BC, O_3) into the air can cause changes to the climate.

- Improve knowledge of the impacts of climate change on human health and the environment in the Megalopolis region, enhancing the ability of the state and local air quality managers to consider climate change in their decisions to protect air quality and to reduce the impacts of a changing climate, as well as the communities to address climate change effectively and sustainably.
- Integrate climate change mitigation and emission inventories with air quality management, as has been done in Mexico City.
- Quantify the health and economic benefits of reducing emissions of air pollutants and greenhouse gases.
- Provide tools and resources to develop a more sustainable energy system.
- Evaluate how different multipollutant/multisector control strategies can affect greenhouse gases and other air pollutant emissions.
- Develop evidence-based information and resources to inform the public and the communities to better prepare for potential climate threats created by wildfires, floods, droughts, and other extreme events, particularly on the most vulnerable populations.

<u>Impacts of air pollution</u>

Air pollution adversely affects human health, causes regional-scale deterioration of visibility and acid deposition, damages crops and the ecosystems. Most studies in Mexico have focused on understanding the impacts of air pollutants on human health. There are information gaps about the impacts on crops, forests, ecosystems, cultural heritage, and public and private infrastructure. Policies and programs for the control of air quality in the Megalopolis have incorporated some of the results of health studies on particulate matter and O_3. However, key questions and issues remain about the relationship between chronic and acute health effects, which are exacerbated by exposure to poor air quality, and the quantification of the costs and health benefits of control of the main emission sources. In section 3.4 above, the challenges and opportunities that exist to improve our knowledge of the impacts on health and ecosystems in the Megalopolis due to air pollution were described in detail. Some of the research needs that the CAMe should promote for the development of programs that improve the estimation of these impacts are described below.

- Provide adequate resources for research on air pollution and health.
- Generate standards and regulations for other environmental toxins of interest to the region, for example, benzene, polyaromatic hydrocarbons, among others.
- Carry out more studies on particle composition to estimate their health risks.
- Strengthen and improve air pollution and health surveillance systems.
- Strengthen studies on the impacts and benefits of air quality management programs on health.

- Generate scientific knowledge about the impacts of air pollution on ecosystem, forests, vegetation and crops.
- Generate evidence on the effects of acid rain on crops, bodies of water, cultural heritage, and public and private infrastructure.

Communication, capacity building, and stakeholder engagement

The success and sustainability of environmental policies depend on high levels of citizen awareness and the informed participation of stakeholders. Permanent changes in attitudes and behavior of the population require the development of an environmental culture and the improvement in education. Many policies will not work unless stakeholders have ownership and share responsibility for their implementation. Their participation can also provide support for unpopular but cost-effective measures adopted in the public interest, especially if these measures are transparent to the public. It is essential to improve the capacity of human resources necessary to diagnose environmental problems, as well as to formulate, execute, and evaluate the policies and programs aimed at improving air quality. More highly trained personnel will enhance the performance of government, the private and academic sectors, and non-governmental organizations. The CAMe should be a leader in air quality management, promoting the implementation of the following recommendations:

- Support the ongoing educational activities of the entities of the Megalopolis aimed at raising environmental awareness of the general public.
- Allocate financial resources for environmental education programs.
- Support air pollution research at universities and government institutions to strengthen environmental management capacity in federal, state, and local government agencies, as well as in the industrial and academic sectors.
- Develop evidence-based information and resources to inform the public and the communities to better prepare for potential climate threats created by wildfires, floods, droughts, and other extreme events, particularly among the most vulnerable populations.
- Involve stakeholders and the general public in the design and implementation of emission reduction strategies, including development of information campaigns about the benefits of reducing emissions for the population.
- Involve communities and non-governmental groups in studies of monitoring and detection of high pollution areas through the use of low-cost sensors.

4. CONCLUSIONS

Starting in the 1980s, air quality improvement programs were based on scientific, technical, social, political, and economic considerations, significant progress has been made in improving air quality in the MCMA, as evidenced by the substantial reduction in concentrations of criteria pollutants. However, O_3 and $PM_{2.5}$ concentration trends have stalled, and recent evidence suggests that production of secondary pollutants has increased, indicating that there is still work to be done before it meets current legal limits for the protection of the health of the population.

The Megalopolis includes the most important population centers in the seven entities in the center of the country, where the phenomenon of population growth and urban space has not been homogeneous and has frequently resulted in areas of lower population density and in the need to travel long distances. Although CAMe was established to coordinate regional policies and programs, the different administrative and legislative jurisdictions, as well as the disparity in the available resources, remain a constant management challenge. There are severe limitations in the monitoring of air quality, development of emission inventories, and air pollution studies in the states, making it difficult to assess regional air quality and the impacts of pollutants in the region. The MCMA and the other entities of the Megalopolis face additional challenges due to urban warming and temperature changes associated with global climate change, as well as the impact of the COVID-19 pandemic.

To address the multiple challenges of air pollution, climate change, and health protection facing the Megalopolis, it is essential to collaborate with national and international experts in atmospheric sciences, public health, social and political sciences, and economics to engage in interdisciplinary research that leads both to holistic assessments of complex environmental problems and to the development of practical strategies and cost-effective solutions to protect public health and the ecosystem. In addition, it will be necessary to develop strategies to overcome the social, economic and political barriers characteristic of megalopolitan problems, including political commitment and follow-up, institutional frameworks, policies and instruments with clear objectives and priorities, greater knowledge about the impacts and solutions, access to adequate financial resources, monitoring and evaluation, inclusive governance processes, consultation with relevant stakeholders and public disclosure.

While the right science and well-chosen technologies can lead the way toward corrective regulatory action, no amount of science and technology can help without strong government commitment. Political leadership is needed to effectively implement integrated megalopolitan policies passing through overlapping and conflicting jurisdictions in the Megalopolis on short-term horizons. A successful result would be to arrive at harmonized control strategies that are effectively implemented and adopted by society.

CHAPTER 1. INTRODUCTION

1.1. Background

With over twenty-one million inhabitants, the Mexico City Metropolitan Area (MCMA) is one of the largest megacities of the world and the most populous metropolitan area in North America (United Nations, 2018a; 2018b). Mexico City has undergone massive transformation in urbanization and demographics throughout its history (Lezama et al., 2002). The population of the Valley of Mexico went from less than 3 million inhabitants in 1950 to more than 18 million in the year 2000, covering an extension of ~ 1500 km^2; which corresponds to an approximate increase of six times in fifty years. The expansion pushed the urban area beyond Mexico City and into the State of Mexico as well as some parts of the State of Hidalgo, forming the Mexico City Metropolitan Area (MCMA) (Molina and Molina, 2002). The population growth rate of Mexico City has steadied since 2000, while the urban population of the State of Mexico has increased; therefore, more municipalities of the State of Mexico have been added to the MCMA over the years. Currently, the metropolitan area has more than 21.7 million inhabitants, of which 9.0 million live in Mexico City and 12.6 million in fifty-nine municipalities of the State of Mexico and the municipality of Tizayuca, Hidalgo (SEDEMA, 2021a). The neighboring metropolitan areas (Puebla, Tlaxcala, Cuernavaca, Pachuca, and Toluca) have also shown increasing demographic growth. This multiple expansion has produced a contiguous urban complex known as the Mexico "Megalopolis" that include Mexico City and the contiguous municipalities from five states (Mexico, Puebla, Tlaxcala, Morelos, and Hidalgo) as well as the state of Querétaro, with a population estimated at approximately thirty-five million (INEGI, 2021).

In the 1980s, rapid population growth, uncontrolled urban expansion, increased energy consumption and motorization, a constrained basin surrounded by mountains at high altitude and an intense solar radiation combined to cause serious air pollution problems for the metropolitan area. The air-quality monitoring network, established in the late 1980s, revealed high concentrations of all criteria pollutants,[1] with ozone (O_3) peaked above 300 ppb for 40-50 days a year, which at that time placed Mexico City air pollution problems among the worst in the world (UNEP-WHO, 1992). In response to growing public concerns about worsening air quality, the Mexican government announced emission reduction actions and strengthened the legal framework of the General Law of Ecological Equilibrium and Environmental Protection (*Ley General del Equilibrio Ecológico y la Protección al Ambiente* or *LGEEPA*) that defined responsibilities at federal, state, and local government levels (DOF, 1988). During the 1990s, the federal government established several administrative agencies to address environmental issues, including the Metropolitan Environmental Commission (CAM, *Comisión Ambiental Metropolitana*) responsible for coordinating the various levels of government dealing with metropolitan

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[1] Criteria pollutants are air pollutants for which acceptable concentration limits have been set on the basis of available information on health effects of each pollutant (see Table 1.1).

environmental problems (DOF, 1996). An Environmental Trust Fund for the Valley of Mexico *(Fideicomiso Ambiental para el Valle de México)* was created to support CAM projects through the application of a surcharge of gasoline sold in the MCMA. In 2013, CAM was replaced by the Environmental Commission of the Megalopolis (CAMe, *Comisión Ambiental de la Megalópolis*) (DOF, 2013).

One of the major activities undertaken by the environmental authorities in the MCMA is the collaboration with national and international scientific and technical experts, including integrated assessment of the air quality in the MCMA and intensive field measurement campaigns (Molina and Molina, 2002; Molina et al., 2007; Molina et al., 2010). Scientific research has played an important role in providing the environmental authorities with essential understanding of the emission sources of pollutant species and their transport and transformation in the atmosphere, their effects on human health and the environment, and identification of effective emission reduction strategies. The key findings and policy implications from these collaborative studies have been incorporated in the design of comprehensive air quality improvement programs (ProAire, *Programa Para Mejorar la Calidad del Aire*).

After three decades of comprehensive air quality management programs based on scientific, technical, social, and political considerations, Mexico City has managed to drastically reducing air pollutants and improving public health. The atmospheric concentrations of lead (Pb), sulfur dioxide (SO_2) and carbon monoxide (CO) were significantly reduced and are below the current air quality standards. The concentrations of O_3, PM_{10} (particles with diameter of 10 micrometers and smaller) and $PM_{2.5}$ (particles with diameters of 2.5 micrometers and smaller) have decreased , but they are still at levels above the respective air quality standards.

As in the case of some other large cities around the world, substantial improvements in air quality in the MCMA have not been achieved recently (Molina, 2021; Molina et al., 2019). Concentration trends of O_3 and fine particles have stalled, and recent severe air pollution episodes suggest that the production of secondary pollutants has increased under an expanding urban sprawl, increasing vehicular fleet, and changing climate. The worse air pollution episodes are associated with regional meteorological events that suppress the ventilation of the city basin and affect the evolution of the planetary boundary layer, atmospheric recirculation, and accumulation of locally emitted and produced pollutants. In addition, regional wildfires caused by periods of increasingly frequent and intense droughts induce severe episodes of particle pollution.

Recently, the lockdown measures enacted in response to the COVID-19 pandemic demonstrated that even drastic reductions in economic activities and vehicular traffic had relatively minor impacts on ozone levels. This experience has profound implications for air quality management since basic control policies are aimed to reduce emissions from traffic and industry.

Mexico City has a robust air quality monitoring network and an emissions inventory that is updated biennially, which provide the necessary data for daily air quality forecasting and supporting air quality management. Nevertheless, most of the current air pollution mitigation strategies in the MCMA are still based on scientific findings from the MILAGRO field campaign that took place in 2006 (Molina et al., 2010). To guide new policies to improve air quality in the Megalopolis region, updated and locally generated scientific information is needed on changes in emission profiles resulting from new regulatory measures and the use of advanced technology, changes in urban micrometeorology caused by growing urbanization, the influence of regional air pollution, and changes in the atmospheric physical and chemical processes.

To achieve this objective, the Molina Center for Strategic Studies in Energy and the Environment (MCE2) has prepared this document, which includes the diagnosis of the current technical and scientific studies on emerging sources of emissions, monitoring and measurements of air quality in the Megalopolis region, changes in the atmospheric chemistry over the years, the impacts of pollutants on public health and climate change, and the impacts of COVID-19 pandemic on air quality.

The document is based on the results of the review and analysis of recently published scientific articles and relevant technical reports, and also integrates the key findings of the "Virtual workshop: Diagnosis of current knowledge of the scientific bases for air quality management in the Megalopolis region" ("*Taller virtual: Diagnóstico sobre el conocimiento actual de las bases científicas para la gestión de la calidad del aire en la región de la Megalópolis,*" hereinafter referred to as "the Virtual Workshop"), which took place on April 21-22, 2022.

The virtual workshop was jointly organized by MCE2 and the Executive Coordination of CAMe, with the collaboration of the Secretariat of Environment of Mexico City (SEDEMA, *Secretaría del Medio Ambiente de la Ciudad de México*), the Secretariat of Environment of the State of Mexico (SMAGEM, *Secretaría del Medio Ambiente del Estado de México*), the Ministry of Environment and Natural Resources (SEMARNAT, *Secretaría de Medio Ambiente y Recursos Naturales*), the National Institute of Ecology and Climate Change (INECC, *Instituto Nacional de Ecología y Cambio Climático*), and the Institute of Atmospheric Science and Climate Change (ICAyCC, *Instituto de Ciencias de la Atmósfera y Cambio Climático*) of the National University of Mexico (UNAM, *Universidad Nacional Autónoma de México*). The objective of the Virtual Workshop was to identify recent advances and gaps in scientific and technical knowledge on air quality, and the challenges that decision makers face in implementing improvement policies. The workshop participants included specialists in air pollution issues from academic, governmental, and civil society organizations who presented and discussed the results of their scientific and technical studies, as well as officials from the federal and local agencies who shared their knowledge and the barriers in the implementation of air quality improvement policies. The agenda, list of panelists, and summary of the presentations and discussions are available as supplement (Spanish) to this document.

The following sections present an overview of the current understanding regarding the air quality and management of the MCMA and other regions of the Megalopolis. Detailed descriptions of the current state of knowledge on air quality monitoring are provided in Chapter 2, while characterization of emissions, atmospheric science research, and health impact studies are presented in Chapters 3, 4, and 5, respectively. Chapter 6 describes some of the major air quality management programs implemented in the MCMA and the Megalopolis region. The document concludes by summarizing the challenges and lessons learned in the implementation of emissions control policies in the Megalopolis region, with emphasis on the MCMA, based on the most recent information available (Chapter 7).

1.2. Environmental management institutions in Mexico

In Mexico, the right to clean air and a healthy environment is supported by different levels of Mexican legislations: (a) Constitution: Article 4 recognizes the right to a healthy environment, (b) the recent Constitution of Mexico City: Article 16 guarantees the right to a healthy environment and requires the development of public policies for the protection of the environment, including the atmosphere (CDMX, 2017). The Secretariat of Environment of Mexico City is responsible for the city's environmental programs, including air quality management and climate action plans. Similarly, the environment secretariats of the State of Mexico and State of Hidalgo manage the environmental programs of their respective states. On September 13, 1996, the Coordination Agreement was signed through which the Metropolitan Environmental Commission (CAM, *Comisión Ambiental Metropolitana*) was created, as a coordination body for the planning and execution of actions related to the environment in the metropolitan area, comprised of the sixteen territorial demarcations (or boroughs) of the Federal District and the eighteen municipalities of the State of Mexico, known as the Metropolitan Zone of the Valley of Mexico (ZMVM, *Zona Metropolitana del Valle de México;* hereinafter referred to as the Mexico City Metropolitan Area, MCMA) (DOF, 1996). To address the environmental problems registered in the MCMA, the CAM was supported by the creation of the Environmental Trust 1490 (FIDAM 1490, *Fideicomiso Ambiental 1490*) to "Support Programs, Projects and Actions for the Prevention and Control of Environmental Pollution in the Metropolitan Area of the Valley of Mexico," which was funded with resources from a surcharge on gasoline sold in the region.

Given the expansion of urbanizations in the central region of the country and the identification of the importance of the interrelationship in the environmental problems of the region, CAMe emerged to address in a coordinated manner the environmental policy between the Federal, states and Mexico City governments. It was created in August 2013 as a coordination body for the planning and execution of policies, programs, projects and actions regarding environmental protection, preservation and restoration of the ecological balance, in the area that makes up the Megalopolis of central Mexico. It is made up of seven federal entities: Mexico City and the states of Hidalgo, Mexico, Morelos, Querétaro, Puebla and Tlaxcala, as well as four Ministries of the federal government: The Ministry of the Environment and Natural Resources (SEMARNAT, *Secretaría de Medio Ambiente y Recursos Naturales*), the Agrarian, Territorial and Urban Development (SEDATU, *Desarrollo Agrario, Territorial y Urbano*), Infrastructure, Communications and Transport (SICT, *Infraestructura, Comunicaciones y Transportes*) and HEALTH (*SALUD*). Its Governing Body is made up of the Heads of the federal Ministries, the Governors of the states and the Head of Government. It has Trust 1490 (FIDAM 1490) to support the Environmental Programs, Projects and Actions of the Megalopolis, which is funded by $5.00 pesos from each vehicle verification carried out in the entities' verification centers.

In addition to the local environmental agencies, at the federal level, SEMARNAT is responsible for the protection and management of natural resources and enforcement of environmental laws.

The INECC offers technical support to local monitoring systems and administers the National Air Quality Information System (SINAICA, *Sistema Nacional de Información de la Calidad del Aire*), while the Ministry of Health (*Secretaría de Salud*) defines the Official Air Quality Standards that regulate the seven criteria pollutants by setting maximum permissible concentrations. The National Centre for Disaster Prevention (CENAPRED, *Centro Nacional de Prevención de Desastres*) is responsible for risk management and disaster prevention in Mexico to reduce public exposure to meteorological, hydrological, geological, and chemical hazards such as tropical storms, floods, earthquakes, volcanic eruptions, and chemical releases. The National Meteorological Service (SMN, *Servicio Meteorológico Nacional*) of the National Water Commission (CONAGUA, *Comisión Nacional del Agua*) provides forecasts and warnings on weather condition, as well as information on meteorology and climatology for the entire country, to support decision making.

1.3. Population and urban development of the MCMA and the Megalopolis

Currently, the MCMA consists of sixteen boroughs (*alcaldías*) of Mexico City with 9.04 million inhabitants and occupying an area of 1,495 km^2, 12.5 million inhabitants in the fifty-nine municipalities of the State of Mexico covering an area of 6,295 km^2, and 130,000 inhabitants in the municipality of Tizayuca in the State of Hidalgo in an area of 76.8 km^2 (SEDEMA, 2021a). Urban expansion of the MCMA has produced the Megalopolis, made up of seven entities in central Mexico (Mexico City and the states Mexico, Puebla, Tlaxcala, Morelos, Hidalgo and Queretaro), with an estimated population of about thirty-five million (INEGI, 2021).

Figure 1.1 shows a map of the Megalopolis. The combination of continued urban expansion and the growth of economic activities has induced the daily movement of large number of people and goods, as well as substantial changes in land use in the region, leading to increased demand for energy.

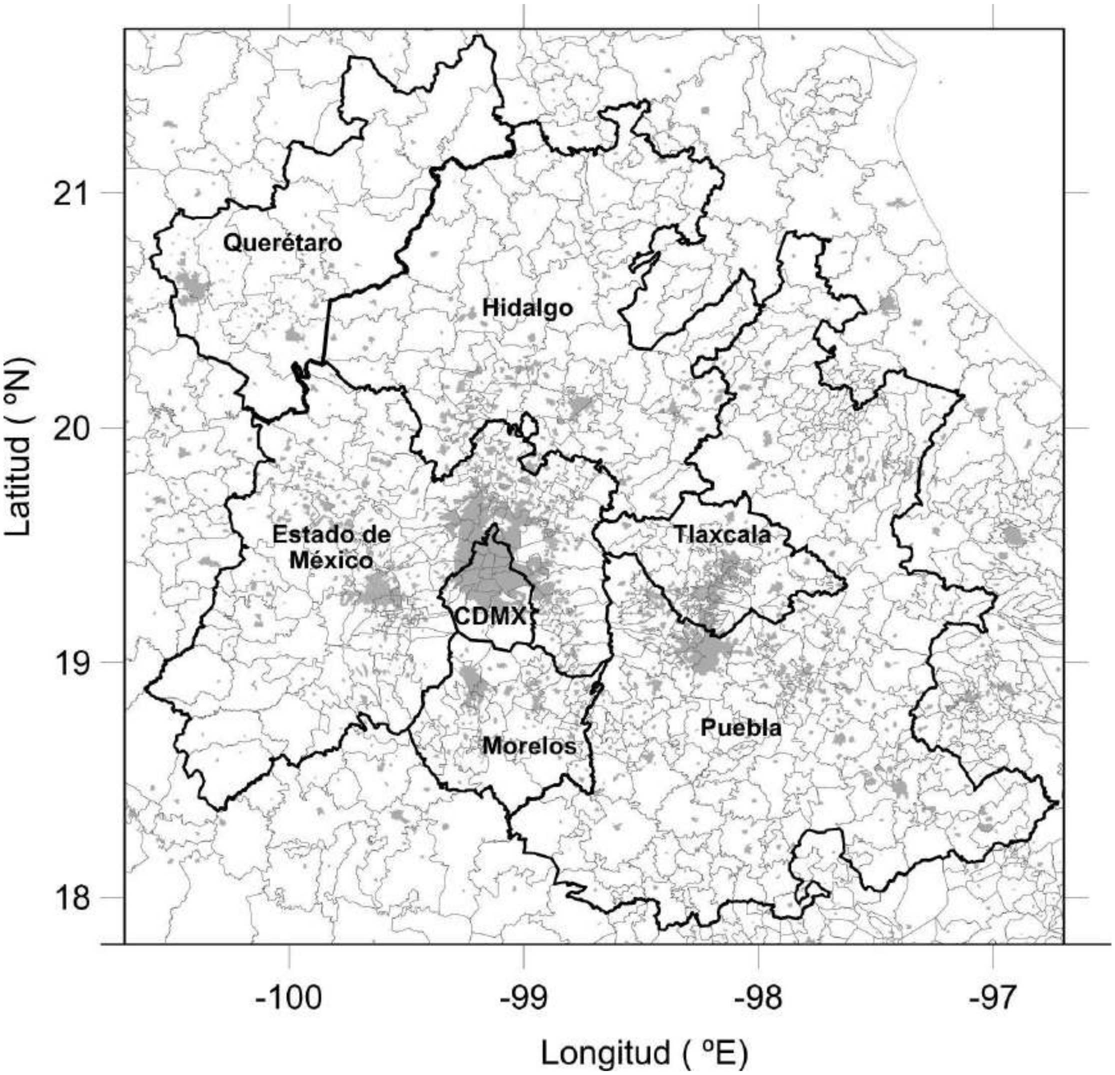


Figure 1.1. Map of the Megalopolis, state boundaries are indicated with a thick black line, while the municipalities with thinner lines, the built-up areas are highlighted with gray shading.

1.4. Topography and meteorology of the MCMA and the Megalopolis region

The topography and meteorology of the MCMA contribute substantially to the problem of air pollution. The MCMA lies in an elevated basin at an altitude of 2240 m above mean sea level (masl) and is surrounded by mountains and volcanoes on three sides, with an opening in the north to the Mexican Plateau and a mountain gap to the southeast. The mountains, together with frequent thermal inversions, trap pollutants within the basin. The high elevation and intense sunlight also contribute to the photochemical processes that drive the formation of O_3. In this geographical setting, the metropolitan area with over 21.7 million residents, 6.0 million vehicles, 1,900 regulated industries, 2,800 regulated commerce and services, and 6.3 million household, consume a large amount of fossil fuels, emitting thousands of tons of pollutants into the atmosphere, which can react to generate other pollutants that may be more dangerous to public health than the original pollutants.

The MCMA has a subtropical highland climate: a cool dry season from November to February is followed by a warm dry season until May and a rainy season from June to October. The semi-closed basin, together with its altitude and latitude, induce the meteorological factors that characterize each of the seasons throughout the year in the region. The hot and dry season is characterized by high-pressure systems with clear skies, high solar radiation, and weak wind most of the day, promoting photochemical processes that form O_3 and other oxidants, as well as increase secondary aerosol loadings through chemical reactions, dust, and biomass burning; in addition, the prevailing wind pattern causes the stagnation of pollutants in the southern area of the basin. Weak winds and strong temperature inversions at night also lead to high primary pollutant concentrations during rush hour that continue into the morning, followed by very rapid boundary layer growth to about 2 to 4 km in the early afternoon (Whiteman et al., 2000). The high elevation and the basin-mountain circulation ventilate the basin effectively; consequently, there is relatively little recirculation or day-to-day carry-over of pollutants within the basin (de Foy et al., 2006). The cool dry season has stronger surface inversions and higher morning concentrations of primary pollutants. The rainy season has lower concentration of particulate matter (PM) but continues to have high O_3 concentration because of intense photochemical reactions occurring prior to the precipitation in the afternoon. Thus, high O_3 episodes can occur throughout the year in the MCMA (Molina and Molina, 2002). A more detailed description of the meteorology and atmospheric dynamics is provided in Chapter 2.

1.5. Infrastructure and Air Quality Management Tools

Since the 1990s, the Mexican government has made significant progress in improving the air quality of the MCMA by developing and implementing successive comprehensive air quality management programs (ProAire) that combined regulatory actions with technological changes and were supported by scientific research. The government has established standards for air quality, vehicle emissions and fuel quality, developed an air quality monitoring network, built emission inventories, invested in a forecast model, and supported research in atmospheric sciences and health effects. The combined information on emissions inventory, land cover and urban morphology, meteorology, and atmospheric chemistry makes it possible to develop air quality models and use them as a tool for forecasting potential air pollution episodes, as well as evaluating past episodes and the efficiency of control measures.

Air quality standards

Ambient air quality standards or norms define the pollutant levels that should not be exceeded if public health is to be protected, they provide an important management tool that can be used progressively to improve air quality. Since 1987, the World Health Organization (WHO) has produced air quality guidelines designed to inform policy makers and to provide appropriate targets in reducing the impacts of air pollution on public health. The standards are strengthened over time as more information becomes available regarding the effects of public exposure to harmful pollutants.

In 1994, the Mexican government established the first ambient air quality standards (NOMs, *Normas Oficiales Mexicanas*) for O_3, CO, nitrogen dioxide (NO_2), SO_2, Pb, and PM_{10} to protect the public from exposure to high level of harmful pollutants (DOF, 1994a, b, c). The standards are defined by the Ministry of Health and are reviewed periodically. The most recent update of the standards was in 2019 for SO_2 (DOF, 2019) and in 2021 for NO_2, PM_{10}, $PM_{2.5}$, Pb, CO, and O_3 (DOF 2021a, b, c, d, e). The current air quality standards for Mexico are presented in Table 1.1.

Table 1.1. Mexico's ambient air quality standards and WHO's air quality guidelines

	Mexico[a]	**Mexico**	**WHO**[b]
Pollutant [Regulatory document]	**Max. Limit (µg m^{-3})**	**Max. Limit (ppm)**	**Guidelines (µg m^{-3})**
O_3 [NOM-020-SSA1-2021]	176 (1-h mean) 128 (8-h mean)	0.090 (1-h mean) 0.065 (8-h mean)	100 (8-h mean) 60 (peak season)[c]
PM_{10} [NOM-025-SSA1-2021]	70 (24-h mean) 36 (ann mean)		45 (24-h mean) 15 (ann mean)
$PM_{2.5}$ [NOM-025-SSA1-2021]	41 (24-h mean) 10 (ann mean)		15 (24-h mean) 5 (ann mean)
SO_2 [NOM-022-SSA1-2019]	196 (1-h mean) 105 (24-h mean)	0.075 (1-h mean) 0.040 (24-h mean)	40 (24-h mean)
CO [NOM-021-SSA1-2021]	30 mg m^{-3} (1-h mean) 10 mg m^{-3} (8-h mean)	26 (1-h mean) 9 (8-h mean)	4 mg m^{-3} (24-h mean)
Pb [NOM-026-SSA1-2021]	0.5 (ann mean)		--
NO_2 [NOM-023-SSA1-2021]	752 (1-h mean) 39 ann mean)	0.106 (1-h mean) 0.021 (ann mean)	25 (24-h mean) 10 (ann mean)

[a] Air quality standards for O_3, SO_2, NO_2, and CO in Mexico are reported in parts per million (ppm); they are converted to µg m^{-3} for comparison at a reference temperature of 298 K and barometric pressure of 1 atm.

[b] WHO Air Quality Guideline (AQG) level (WHO, 2021).

[c] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

Air quality monitoring network

The Mexico City atmospheric monitoring system (SIMAT, *Sistema de Monitoreo Atmosférico*) has a wide geographic coverage and good data collection capacity through its four networks (automatic, manual, atmospheric deposition, and meteorological). It is one of the most advanced monitoring networks in Latin America.

Since the 1960s, there have been limited measurements of pollutants, particularly SO_2 and total suspended particles (TSP) (Bravo 1960). The government of then Federal District started monitoring air quality in the 1970s with a manual network of twenty-two stations for SO_2 and TSP. The automatic air-quality monitoring network, established in the late 1980s, revealed high concentrations of all criteria pollutants, placing Mexico City air pollution problems among the worst in the world. After more than three decades of comprehensive air quality management programs, it has made important advances to reduce air pollution. The atmospheric concentrations of Pb, SO_2, and CO decreased significantly and are below the current air quality standards. However, although O_3, PM_{10}, and $PM_{2.5}$ concentrations were also decreased substantially, they are still at levels that are above the respective air quality standards. Furthermore, no significant downward trend has been observed for O_3 and $PM_{2.5}$ since 2006, and several episodes of severe pollution have been observed in recent years.

Because of the high cost associated with the infrastructure for setting up an air quality monitoring network, the concentrations of many criteria pollutants are not routinely measured in the surrounding region of the MCMA. The MCMA has an extensive air quality monitoring network with forty-four stations (of which thirty-four continuously measure criteria pollutants) that covers most of the territory of Mexico City and a fraction of the conurbation area of the State of Mexico. The other entities also have monitoring systems, but with different degrees of maturity, infrastructure and data quality. Monitoring is carried out mainly in urban areas and there is little information on the situation in rural areas, conservation land and small population centers. A common problem in all monitoring systems is the lack of economic, technical and human resources that cause deficiencies in periodic operation and maintenance activities. Recognizing the above, with the purpose of strengthening the infrastructure of the monitoring systems, contributing to the improvement of data quality and creating a Megalopolitan Air Quality Monitoring System, CAMe carried out the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis (*Programa de Reforzamiento de las Capacidades de Monitoreo de la Calidad del Aire en la Megalópolis*), with an investment of 150 million pesos from the National Infrastructure Fund (FONADIN, *Fondo Nacional de Infraestructura*).

Recent developments in sensor technology have improved the performance of low-cost monitors and, if they are calibrated against reference monitors at regular intervals, could expand the capability of existing networks. The data obtained can potentially complement the information provided by regulatory networks and help in detecting local hot spots, increase spatial density of the network, provide data at micro-scale level or in places outside the spatial coverage of the network, assess the impacts close to the source and increase the spatial representativeness of the monitoring stations. They can be used to obtain indicative air quality data in places where it is difficult to install regulatory grade stations, in remote sites, in agricultural and rural areas. However, it is important to note that, for management purposes, these devices are an exploration tool and under no circumstances do they replace regulatory monitoring. Currently, SEDEMA, in coordination with the ICAyCC-UNAM, are exploring the characteristics of these devices with a view to developing future applications of possible interest to environmental authorities (Grutter et al., 2023).

The increasing availability of satellite data and a new generation of air quality monitoring satellite are providing scientists and policy makers with additional information about the levels of criteria pollutants (see for example, NASA, 2022a). A new NASA Tropospheric Emissions: Monitoring of Pollution (TEMPO) spectrometer, scheduled for launch in April 2023, will provide hourly daylight measurements of solar backscattered radiation at high spatial resolution covering the North American continent (NASA, 2022b). These unprecedented measurements will enable robust retrievals of major air pollutants, which will greatly enhance the monitoring of the rapidly changing emissions and atmospheric chemistry that govern air quality conditions.

In Mexico, the Spectroscopy and Remote Sensing group of the ICAyCC-UNAM is the main research team dedicated to the analysis of satellite data and its validation. Currently, Mexico City and CAMe are exploring the potential of TEMPO observations to monitor air quality in regions that currently lack monitoring systems and in applications to evaluate impacts on public health and ecosystems.

Detailed descriptions of the air quality trend in the MCMA and other states of the Megalopolis are presented in Chapter 2.

Emissions inventory

Emissions inventory is an essential air quality management tool to evaluate the progress of emission-control strategies and to plan future actions. The MCMA has developed emissions inventory since the late 1980s, in which mobile source emissions were estimated by traffic counts while industrial emissions were quantified by voluntary survey (Molina and Molina, 2002). Since 1994, the emissions inventory covers four categories: Point sources (industry), area sources (services and residential), mobile sources (transportation), and natural sources (vegetation and soil). The MCMA emissions inventory is well developed and complies with the BASIC+ certification issued by C40. The inventory is updated every two years and includes criteria and toxic pollutants, black carbon (BC), and greenhouse gases, as well as the diurnal and spatial variability of the emissions. The inventory estimates emissions of about 1900 regulated industries, and about 2800 regulated commercial and residential activities, in addition to contributions from vehicular traffic, aviation operations, waste and wastewater management, and natural sources (that is, biogenic sources) over a gridded area of 1 km × 1 km cells (as needed for modeling purposes).

The 2018 MCMA emissions inventory includes the improvements introduced in the 2016 version and takes up the estimates for Mexico City and its metropolitan area, unlike the previous document that only included Mexico City. Estimates from this inventory were used to inform emission reduction strategies and the prioritization of ProAire 2021-2030 measures and actions (SEDEMA et al, 2021). The 2018 emissions inventory was released in 2021 and is available at the SEDEMA website (SEDEMA, 2021a). The 2020 emissions inventory will be released in the summer of 2023.

At the federal level, the first National Emissions Inventory of Mexico (INEM) was created for the base year of 1999 as a result of the work group of the General Directorate of Air Quality Management and Pollutant Emissions and Transfer Registry (DGGCARETC, *Dirección General de Gestión de la Calidad del Aire y Registro de Emisiones y Transferencia de Contaminantes*) of the SEMARNAT. In the elaboration of the INEM, the SEMARNAT working group has traditionally collaborated with other agencies dependent on the Federal Government and environmental authorities of the states and municipalities, as well as with academic, research, and non-governmental organizations. Subsequent INEM estimates have been made for the base years 2005, 2008, 2011, 2013, 2014, and 2016, seeking in each version to improve the accuracy of the information obtained by updating the emission models, emission factors, and activity data. Recently, the DGGCARETC was replaced by the General Directorate for Industry, Clean Energies and Air Quality Management (DGIELGCA, *Dirección General de Industria, Energías Limpias y Gestión de la Calidad del Aire*). Additionally, with the support of FIDAM 1490, the DGIELGCA updates the 2018 inventory, which will include an update of the MOVES-Mexico models. In addition, INECC prepares the National Inventory of Emissions of Greenhouse Gases and Compounds (INEGYCEI, *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*).

Sources of emissions and the challenges to improve the estimation of emissions in the Megalopolis are presented in Chapter 3.

Air quality modeling and forecasting

Numerical modeling is an essential tool to help decision makers in designing air quality policies and in evaluating control measures under present and future emission and climatic scenarios, as well as air quality forecasting. The development and success of such model depends on reliable ground-based and satellite air quality monitoring observations, accurate high-resolution emission estimates, and a strong knowledge of the local atmospheric chemistry and physics.

Real-time air quality forecast information plays a relevant role in informing the public about potentially harmful concentrations of pollutants such as O_3, PM_{10}, $PM_{2.5}$ and NO_2. This information allows the government and the public to anticipate precautionary measures, such as restricting vehicle circulation and minimizing outdoor activities to limit their exposure to predicted unhealthy levels of air pollution.

Currently, Mexico City government has implemented an air quality forecast system for the MCMA to alert the public about expected O_3 and $PM_{2.5}$ pollution levels up to 24 hours in advance. The system is also used in evaluating emission reduction policies for air quality improvement and other co-benefits. The forecast has been published daily since 2017. Its performance is periodically evaluated against network observations, the results indicate adequate performance for O_3 and moderate for $PM_{2.5}$, but it presents difficulties in identifying extreme pollution events. At the Megalopolis level, substantial challenges remain in implementing air quality forecasting system due to limited capacity for air quality monitoring and emissions inventory development, as well as scarce qualified technical personnel capable of participating in air quality modeling and forecasting activities. Taking this into account, CAMe has considered the need to develop an air quality modeling and forecasting system for the central region of the country, which includes all entities of the Megalopolis. With the collaboration of the ICAyCC-UNAM, it intends to develop and implement a modeling and forecasting system using state-of-the-art models, taking advantage of the supercomputing infrastructure of its data center. This development will benefit from the experience and knowledge of the ICAyCC-UNAM scientists who have developed a forecasting system for central Mexico. This effort will start with an air quality forecasting course-workshop aimed at the entities of the Megalopolis.

Chapter 4 describes some recent modeling studies conducted in the MCMA, including several on the impact of COVID-19 lockdown on air quality.

1.6. Atmospheric scientific research in the Megalopolis

The study of atmospheric processes constitutes a fundamental activity to understand the impacts and evaluate the best options for mitigating air pollution. Scientific research has played an important role in assisting the environmental authorities of the MCMA in the characterization of the emission sources of polluting species and their transport and transformation in the atmosphere, identifying effective emission reduction strategies, and monitoring the progress of the regulations that are already in place to ensure that programs are successfully implemented.

During 1990-1994, the Mexico City Air Quality Research Initiative (MARI) project collected surface and vertical profile observations of meteorology and pollutants to support modeling studies (Streit and Guzman, 1996). In February - March 1997, the Aerosol and Visibility Evaluation (*Investigación sobre Materia Particulada y Deterioro Atmosférico*, IMADA-AVER) campaign generated comprehensive meteorological measurements in the basin, and provided information on the particulate composition (Doran *et al.*, 1998; Edgerton *et al.*, 1999).

During 1999-2000, the Massachusetts Institute of Technology (MIT) Integrated Program on Urban, Regional, and Global Air Pollution caried out a comprehensive assessment of the MCMA air quality at the request of the Mexican authority to support the design of a new strategic plan for the next 10 years, which provided the scientific foundation for the ProAire 2002–2010 (Molina and Molina 2002; CAM 2002). The integrated assessment involved the participation of multi-disciplinary experts in atmospheric science, public health, social and political studies, and economics from Mexico and the US. The integrated approach emphasized that addressing air pollution problem requires not only an understanding of air pollution science but also how to balance economic, social, political, and technological factors, and how to make decisions in the presence of uncertainty and incomplete data. (Molina and Molina 2002).

The recommendations of the integrated assessment to update and improve the MCMA emissions inventory and to improve the current knowledge of the atmospheric chemistry processes led to two field measurements campaigns, during February 2002 and March 2003 sponsored by the CAM (Molina et al. 2007), and subsequently. the MILAGRO (Megacity Initiative: Local And Global Research Observations) campaign in March 2006 (Molina et al. 2010, Singh et al. 2009). The MCMA-2003 and MILAGRO-2006 campaigns provided wide-ranging meteorological, gas, and aerosols measurements, significantly improved the understanding of the meteorological and photochemical processes contributing to the formation of O_3, secondary aerosols, and other pollutants, as well as their transport and transformation into the MCMA’s atmosphere.

Characterization of gases and particulate matter in the Megalopolis

Since the MILAGRO campaign, relatively few field studies have been conducted in the MCMA and the other region of the Megalopolis, although some special studies have been carried out by SIMAT, non-governmental organizations, academics and independent researchers. Several projects on the characterization of gases and particulate matter in the MCMA and in other states of the Megalopolis are described in more detail in Section 4.3 of Chapter 4.

Current observations indicate that key pollutants have not decreased to acceptable levels. Furthermore, the atmospheric concentrations of pollutants such as O_3 and secondary aerosols are increasing in recent years (Velasco & Retama, 2017; Zavala et al., 2020), suggesting the need to update the state of scientific knowledge of the processes that control the formation, transport, and fate of these pollutants (Molina et al., 2019; Velasco et al., 2021; Molina, 2021).

Short-lived climate forcers: linking air quality and climate change

Although air pollution and climate change are closely interrelated with respect to sources, atmospheric processes, and human and environmental effects, air quality and climate change have been treated as two separate and distinct policy issues. Air pollution control strategies have traditionally been focused on reducing emissions of air pollutants that are harmful to public health or damage the environment, while climate change policy has focused on reducing emissions of greenhouse gases, primarily CO_2. Substantial potential benefits and synergies can be realized from integrated strategies that address both issues, achieving co-benefits.

Recently, a few species known as short-lived climate forcers (SLCFs) have received much attention in the climate science community for their role in slowing the rate of near-term climate change from regional to hemispheric scales, in addition to significant benefits to energy efficiency, human health, crop production, and ecosystems. The major SLCFs with lifetimes under a few decades are BC (~ days to weeks), CH_4 (~ a decade), tropospheric O_3 (weeks to months) and some hydrofluorocarbons (HFCs, average 15 years). Due to their nature, these substances can be rapidly controlled and reduced with existing technology providing short-term climate benefits, as well as improving air quality (UNEP-WMO, 2011; UNEP, 2011a, 2011b).

Mexico has undertaken several efforts to assess SLCFs emissions and to foster mitigation measures since 2010 with the study entitled “Emerging topics in climate change: methane and black carbon, possible co-benefits and development of research plans” (INE-MCE2-UNAM, 2011). This was followed by a series of technical workshops and ministerial meetings, leading to first order national planning for SLCFs under the SNAP (Support National Action Planning on Short-Lived Climate Pollutants) initiative of the Climate and Clean Air Coalition (CCAC) in 2013 (MCE2-INECC, 2013). This process led to the development of a research initiative by MCE2 to better characterize the emission sources of SLFCs in the country, including multiple wastewater treatment plants, landfills, research livestock farms, brick kilns, residential cookstoves, on-road and non-road fleets of heavy-duty diesel vehicles. Section 4.5 in Chapter 4 describes the results and lessons learned from some of the measurements conducted specifically in the MCMA and the Megalopolis region.

Urban climatology and air quality

The chemical and physical processes involved in the formation of pollutants that occur in the atmosphere are sensitive to changes in meteorological conditions. Structures such as buildings, roads (asphalt and concrete), and other infrastructures absorb and re-emit the sun's heat more than natural landscapes such as trees, vegetation, and water bodies. Urban areas, where these structures are highly concentrated and greenery is limited, become "islands" of higher temperatures relative to peripheral areas, creating the heat island effects (UHI). The temperature difference between the urban area and the rural surroundings is usually larger at night than during the day and is more evident when the winds are weak. The temperature can also vary within a city; some areas are hotter than others due to the uneven distribution of heat-absorbing buildings and pavements.

The atmosphere of the MCMA has experienced progressive warming in recent decades, possibly because of the synergistic interaction between increased land cover modification, new material used for construction, anthropogenic heat, and changes in temperature associated with global climate change. A similar increasing trend in ambient temperatures has been observed also in other urban regions of the Megalopolis. Although an increase in temperature is possible in the central region of the country because of climate change, little is known about the effects it will have on the meteorology of synoptic, regional, and local scales (SEDEMA, 2021b). Some of the formation processes of secondary compounds (for example, the formation of O_3) are sensitive to climate, therefore, the impacts of climate change are expected to also involve the way pollutants are transformed, dispersed, and deposited.

Despite the significant change in temperature in Mexico City and the pioneering work of Jáuregui (Jáuregui, 1997), currently the study of urban climatology is scarce. Section 4.4 in Chapter 4 describes some of the recent studies that address aspects of interest on the interaction of atmospheric pollution with meteorology, as well as the possible effect of changes in surface ultraviolet (UV) radiation on O_3 formation.

Impact of COVID-19 on air quality in the Megalopolis

Following the detection of the novel coronavirus SARS-CoV-2 in Wuhan, China in December 2019 and the rapid spread of the COVID-19 disease caused by the new virus around the world (WHO 2020a; 2020b), most countries enacted strict measures to contain the spread of the disease to protect the public health, including lockdowns, quarantines, and travel restrictions, reducing global economic activity. The stress from the pandemic and the resulting economic recession have negatively affected the mental health and well-being of the people all over the world. Furthermore, air pollution was found to substantially increases the risk of infection and the severity of COVID-19 symptoms.

In Mexico, the first cases were diagnosed during the last week of February 2020. As a precautionary measure, basic education schools suspended activities starting March 17, 2020. This was followed by partial lockdown measures for some non-essential activities, the suspension of services offered by the public administration and the cancellation of public gatherings of more than 25 people. Given the advance of the pandemic, the authorities applied Phase 3 actions starting April 21, 2020, which implied total ban of any non-essential activity. In Mexico City, the suspension was extended to non-essential industrial and commercial activities, the reduction in services and public transport and the decrease in private vehicles in circulation. In the rest of the entities of the Megalopolis, in addition to suspension of non-essential activities, there was a decrease in the demand for public transport and in the circulation of private vehicles as a result of the “Stay at home” promotion. The reduced motorization and economic activity resulted in the reduction of the concentrations of some pollutants as recorded in the air quality monitoring stations in the MCMA and other entities of the Megalopolis.

An unintended consequence of the restrictions during Phases 2 and 3 was the reduction in emissions from automobiles, industry, and commercial activity, on a scale unprecedented in Mexico, offering atmospheric scientists and air quality managers a unique opportunity to study the effects of extraordinary reductions in anthropogenic activities on air quality. Considering that most long-term pollution reduction strategies and control actions during episodic pollution events are focused on reducing emissions from automobiles and industry, this unplanned experiment was of great value to estimate under real conditions the maximum impact that could be achieved with the current management scheme. Section 4.7 in Chapter 4 describes the impacts of changes in urban activity related to the application of the measures during the COVID-19 pandemic on air quality.

In the Megalopolis region, many activities, such as work and educational activities, were carried out through electronic means, and others used the flexible hybrid working arrangement (face-to-face and remote through videoconferences, email, and telecommunications). Using an indicator of the mobility of people, it was possible to show the drastic reduction in mobility, but also show that some entities and cities in the Megalopolis returned to the pre-pandemic level while others remained at lower levels when some of the confinement restrictions were lifted. This return to the previous motor vehicles circulation conditions also implied the return to the emission levels that existed before the pandemic, and therefore to the previous air quality levels, modulated by other factors such as climatic and meteorological conditions, and the occurrence of forest fires.

1.7. Research on health impacts of air pollution in the Megalopolis

Atmospheric pollutants affect the health of the population and can also damage crops, reducing their yield and increasing the risk to food security. It can also affect forests and ecosystems by reducing the quality and quantity of the environmental services they provide to society. However, most studies in Mexico have focused on understanding the impacts of air pollutants on human health. There are still information gaps about the impacts on crops, forests, ecosystems and cultural heritage and public and private infrastructure.

Air pollution has a range of impacts on public health, including reduced lung growth and function, respiratory infections, and aggravated asthma in children, while ischemic heart disease and stroke are the most common causes of premature death in adults. There is emerging evidence of other effects such as diabetes and neurodegenerative conditions. Evidence on the effect of air pollution and health has led to increasingly large risk estimates even at lower concentrations than previously understood; this motivated the World Health Organization (WHO) to establish stricter values for the Air Quality Guidelines in 2021 (WHO, 2021), as well as the Mexico authorities to update the air quality standards, which are shown in Table 1.1. This becomes even more relevant in the Megalopolis region because it presents significant air pollution problems that are reflected in frequent non-compliance with air quality standards, health impacts, direct and indirect economic costs, and damage to ecosystems. The health impacts can be exacerbated for the most vulnerable population groups, such as the elderly, pregnant women, children, people with chronic diseases or with weak immune systems.

Chapter 5 reviews the current state of knowledge on the impact of air pollution on public health in the Megalopolis, assess their progress, and the scientific challenges. Some of the results of health studies on particulate matter and ozone have already been incorporated into policies and programs for air quality control in the Megalopolis. However, key questions and issues remain about the relationship between chronic and acute health effects that are aggravated by exposure to poor air quality and the quantification of the health costs and benefits of controlling key emission sources.

1.8. Air quality management programs in the Megalopolis

Air quality management refers to all the activities a regulatory authority undertakes to protect public health and the environment from the harmful effects of air pollution. It is an iterative and dynamic process represented as a cycle of inter-related elements (see Figure 6.1, Chapter 6). Typically, the process starts with a government institution establishing air quality goals, targets, and standards that define threshold concentrations for key pollutant species that will protect public health and the environment. Air quality managers will need to determine emission reductions necessary to meet the standards and objectives by applying various assessment tools, including emission inventories, air quality monitoring, and modeling.

During the development of control strategies, air quality managers should include the required budget, implementation mechanisms, the agencies responsible for the actions, and a schedule of compliance and implementation plans. To successfully achieve the required reductions, they will need to implement the programs and enforce the rules and regulations. Ongoing evaluation is important to assess the effectiveness of the strategies and measure the progress towards meeting air quality goals. Because air quality management typically operates with substantial scientific, technological, and societal uncertainties, it is necessary to continuously review and assess the objectives and the strategies as new information becomes available. In some cases, this might include setting new air quality standards.

The contributions of science and technology are made through monitoring, analysis, research, and development, which provide air quality managers with fundamental knowledge to make informed decisions. Throughout each stage of the process, it is essential to communicate with the public about the state of their air quality.

In the United States, the Clean Air Act (CAA, 1970) provides the legal framework that authorizes the US Environmental Protection Agency (EPA) to set maximum allowable concentrations of six common air pollutants (O_3, CO, NO_2, SO_2, Pb, and PM) by establishing National Ambient Air

Quality Standards (NAAQS). Individual states then develop state implementation plans that show how, with the assistance of national control programs, they will meet these standards through the air quality management program (US EPA, 2022).

In 1994, the Mexican government established the first ambient air quality standards for O_3, CO, NO_2, SO_2, Pb, and PM_{10} with the aim of protecting public health, following the example of the United States (DOF, 1994a, b, c). As described in Section 1.1, the standards are defined by the Ministry of Health and are reviewed periodically.

The federal government maintains a comprehensive air quality management approach through the Air Quality Improvement Program (ProAire, *Programa Para Mejorar la Calidad del Aire*), which responds to the need of each one of the thirty-two states that make up the country to have a preventive and/or corrective instrument in terms of air quality and health protection, as well as to comply with the applicable legal framework in this area. As of 2022, all the states of the Megalopolis have a current ProAire, Puebla's ProAire is in the process of being updated (SEMARNAT, 2022).

Due to the severe air pollution problem in Mexico City identified in the 1980s, the air quality in the MCMA has been the subject of extensive air pollution control efforts over the past three decades. The first air quality management program, Comprehensive Program Against Air Pollution in the MCMA (*Programa Integral contra la Contaminación del Aire* or PICCA), was implemented in 1990 (DDF, 1990) and was replaced by the Program to Improve the Air Quality in the Valley of Mexico (*Programa Para Mejorar la Calidad del Aire en el Valle de México 1995–2000* or ProAire 1995–2000) in 1996 (DDF, 1996). In 2002, the 10-year air quality management program (ProAire 2002–2010) was developed (CAM, 2002), and in 2010, the 10-year air quality management program (ProAire 2011–2020) was enacted (CAM, 2011).

One of the actions of the air quality management programs included the improvement of scientific research through collaboration with national and international scientific and technical experts. One of the examples is the MIT Integrated Program on Urban, Regional, and Global Air Pollution described above (Section 1.6). The assessment results (Molina and Molina, 2002). provided the scientific foundation for the ProAire 2002–2010.

Following the recommendations of the assessment to update and improve the MCMA emissions inventory and the current knowledge of the chemistry, dispersion, and transport processes of the pollutants emitted to the MCMA atmosphere, during February 2002 with the sponsorship of CAM, innovative exploratory field measurements were performed with mobile and fixed site platforms. This was followed by the intensive MCMA-2003 field measurement campaign in the spring of 2003 (Molina et al. 2007). Scientific findings from MCMA-2003 were instrumental in the planning and execution of the MILAGRO campaign in March 2006, the largest and most important study on air pollution in the MCMA to date (Molina et al. 2010, Singh et al. 2009). The scientific findings from the field studies and the policy implications have been incorporated by the Mexican government officials as the scientific basis in the design of Mexico's air quality management program 2011-2020 (ProAire 2011-2020).

In September 2018, SEDEMA sponsored the "Workshop for the Evaluation of ProAire 2011-2020 and Identification of Strategies to Improve CDMX Air Quality" (*Taller para la Evaluación del ProAire 2011-2020 e Identificación de Estrategias para Mejorar la Calidad del Aire de la CDMX)* to evaluate the progress of the air quality management program ProAire 2011–2020 and to identify the strategies for air quality improvement. It was organized by MCE2 and ICM (Iniciativa Climática de México) and included the participation of local governments, national and international scientific and policy experts, and relevant interested stakeholders (SEDEMA 2018**)**. The recommendations were included in the current ProAire 2021-2030, which was published in December 2021 (SEDEMA et al., 2021).

Over the last three decades, the MCMA has made tremendous progress in improving its air quality, after implementing comprehensive science-based management programs The air quality standards and the environmental contingency program were strengthened, recognizing the scientific evidence on health effects associated with exposure to ever lower concentrations of harmful pollutants. Nevertheless, concentrations of PM_{10}, $PM_{2.5}$, and O_3 are still above the respective air quality standards, and possibly have started to rise again. Substantial challenges remain to effectively reduce concentrations of these pollutants to protect the public health and the environment. Furthermore, since population growth, urban expansion, and the high motorization of the metropolitan area and the surrounding Megalopolis region will continue to generate polluting emissions, it is important to advance in the development and implementation of additional policy measures to improve the air quality. It is important to design and implement strategies to reduce the effects of urban heat islands. Both actions can help mitigate climate change. The integration of air quality and climate stabilization goals in the design of environmental policies would be highly beneficial.

To achieve this, it is necessary to strengthen megalopolitan coordination and collaboration in the different tasks related to air quality management, such as atmospheric monitoring, development of the emissions inventory, as well as the design, enforcement, and evaluation of control actions.

Furthermore, a high level of citizen awareness and informed participation of stakeholder will be essential for the success and sustainability of environmental policies. Currently, the government of Mexico City has maintained an extensive communication infrastructure and deploys various strategies to disseminate information to the public. SEDEMA maintains a website that disseminates the air quality index, offers content on various topics related to pollution and air quality (http://www.aire.cdmx.gob .mx/), including infographics, annual reports, open data and a specialized space for children (http://www.aire.cdmx.gob.mx/teporingo/). It also uses mobile platforms and social networks for the dissemination of information. Recently, the CAMe launched the "Pon buen ambiente" campaign available on social networks. The objective is to motivate the population to carry out actions for the benefit of the environment (https://www.portalambiental.com.mx/calidad-del-aire/20201228/pon-buen-ambiente-para-mejorar-la-calidad-del-aire-y-la-salud). The Mexican authorities also launched the Air and Health Index (under NOM-172-SEMARNAT-2019) to communicate the degree of air pollution and the probability of an adverse effect on the health of people exposed to pollutants.

Chapter 6 describes the air quality management programs in the MCMA and the Megalopolis, as well as assesses some of the major programs to improve the air quality and the evolving challenges facing the decision makers.

CHAPTER 2. AIR QUALITY MONITORING IN THE MEGALOPOLIS

The most important objectives of environmental management is to generate the necessary knowledge about the levels, sources, and dynamics of air pollution, so that authorities, policy makers, researchers, and the general public can propose and undertake corrective measures to improve air quality. Monitoring provides the evidence necessary to understand the air quality situation and thus protect the public health. The results of atmospheric monitoring make it possible to evaluate the impact of management strategies and facilitate the design of new control measures. This Chapter describes the existing monitoring networks in the Megalopolis, and based on the data they generate, assess the current situation of air quality in the entities that comprise it. Annex A describes how emerging technologies (that is, low-cost air pollution monitors and satellite observations) could complement air quality monitoring. Annex B presents the time series for the period 2016 to 2020 of the pollutants measured by the monitoring systems of Hidalgo, Puebla, and Querétaro.

2.1. Air quality monitoring in Mexico City and its metropolitan area

2.1.1. Atmospheric monitoring system of Mexico City

Mexico City has a mature and robust system for monitoring air quality. It integrates forty-four monitoring stations, a mobile monitoring station, a control center, laboratories for maintenance and calibration of monitoring equipment, and for speciation and chemical analysis. Its spatial coverage extends beyond the limits of Mexico City and covers a large part of the metropolitan area of the State of Mexico. Together, these components make up the Mexico City Atmospheric Monitoring System (SIMAT, *Sistema de Monitoreo Atmosférico de la Ciudad de México*) and its operation is under the responsibility of the Air Quality Monitoring Directorate (DMCA, *Dirección de Monitoreo de la Calidad del Aire*). SIMAT is the most important source of information on air quality in the metropolitan area of the Valley of Mexico; the quality of its data allows its use both for the purposes of dissemination and information to citizens about air quality, as well as for the needs of scientific work. It operates continuously throughout the year; data on air quality, meteorology, and the ultraviolet (UV) index are disseminated 24 hours a day through its website (www.aire.sedema.cdmx.gob). Its configuration and operation scheme are used as a model by other monitoring networks in the country.

Of the forty-four monitoring sites (June 2022, see Figure 2.1), thirty-four sites correspond to stations for continuous monitoring of criteria pollutants and make up the Automatic Atmospheric Monitoring Network (RAMA). Criteria pollutants are air pollutants for which acceptable concentration limits have been set on the basis of available information on health effects of each pollutant. Table 1.1 in Chapter 1 lists the current pollutants regulated in Mexico: ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particles with a diameter of 10 micrometers or less (PM_{10}), particles with a diameter of 2.5 micrometers or less ($PM_{2.5}$), and lead (Pb).

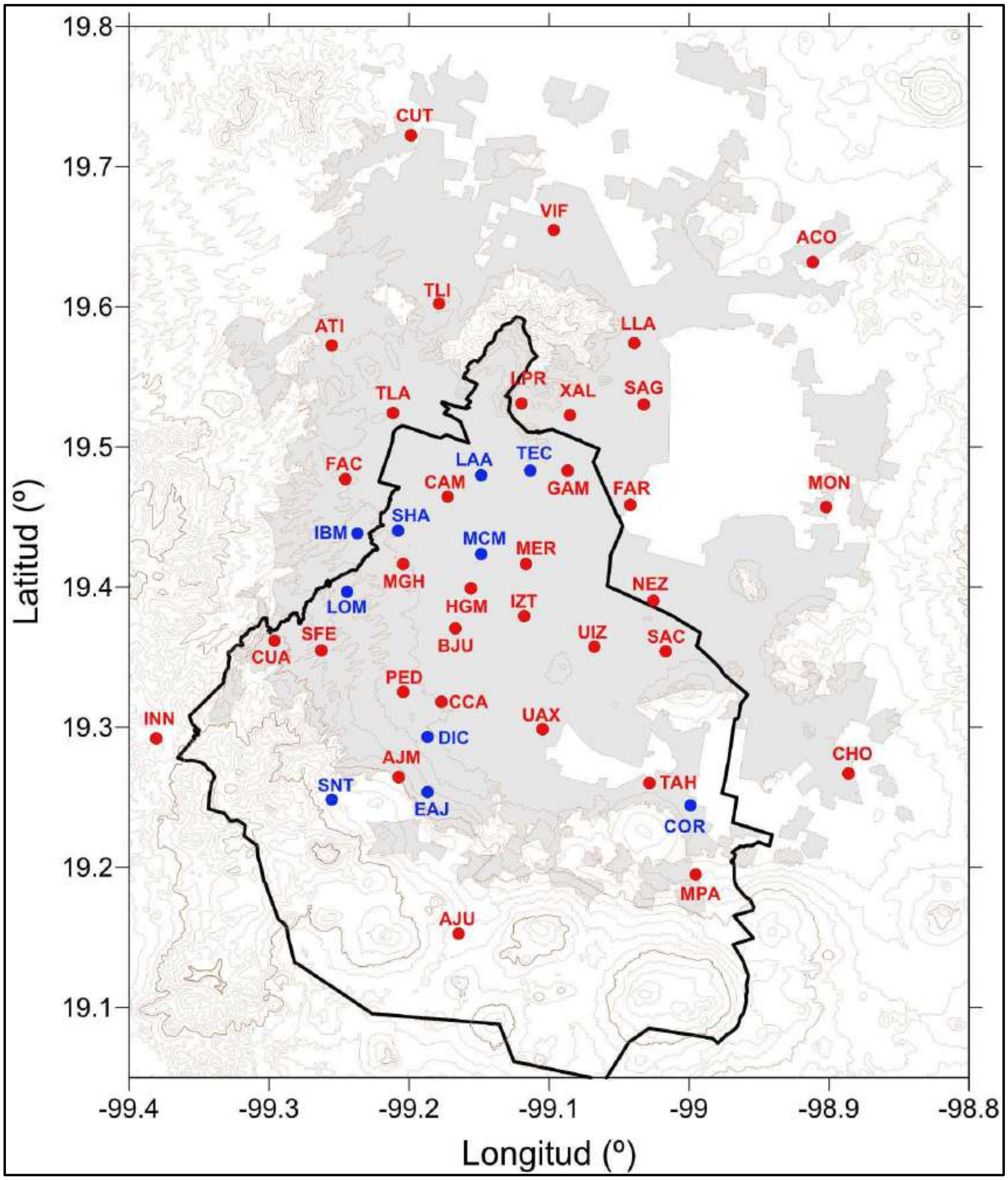


Figure 2.1. Location of the monitoring sites of the Mexico City Atmospheric Monitoring System (SIMAT). The stations of the Automatic Atmospheric Monitoring Network (RAMA) designated for continuous monitoring of criteria pollutants are shown in red, the stations for other purposes are indicated in blue. (Own elaboration with data from the Air Quality Monitoring Directorate, www.aire.sedema.cdmx. Gov.mx).

SIMAT maintains a permanent effort with the objective to generate the necessary information to update existing environmental policies in the city. It has the necessary flexibility to respond to new regulatory management needs. Its configuration ensures spatial monitoring coverage throughout the city and can be quickly adapted to the demands of a dynamic urban environment. The technology and methods used in monitoring comply with current regulatory requirements. Data quality is ensured through a set of quality assurance and control activities at each stage of the monitoring process. Although SIMAT's main responsibility is the continuous monitoring of criteria pollutants, it also contributes to scientific research by supporting research projects and special monitoring campaigns (for example, Molina et al., 2007, 2010, 2019).

2.1.2. Air quality situation according to the monitoring data

Prior to the presence of the COVID-19 pandemic in 2020, the levels of most of the criteria pollutants in the MCMA showed a decreasing trend , except for O_3 and $PM_{2.5}$. In 2020, the actions taken by the authorities to reduce the infection rate of the SARS-COV-2 virus led to a significant decrease in economic and social activities, resulting in significant reductions in emissions and an improvement in air quality. Although the impacts on atmospheric chemistry and public health have not yet been methodologically evaluated, the atmospheric monitoring data showed changes in the composition of the air with a significant decrease in the concentrations of primary pollutants during the most severe phases of the pandemic. Subsequently, with the reactivation of economic activity, pollution levels gradually increased during 2021.

Figures 2.2a and 2.2b show the time series of monthly average concentrations since 2010, for CO and nitrogen oxides (NO_X), respectively. A relevant aspect of the behavior of CO and NO_X levels is related to a significant increase in concentrations with respect to pre-pandemic levels, apparently the concentrations of these pollutants did not recover the downward trend they had prior to the pandemic, and even the statistical indicators for 2022 were similar or higher than those registered in 2018 and 2019.

The levels of O_3 have exhibited little change in the last decade (Figure 2.2c) and the evidence suggests a possible reversal trend, as can be seen in Figure 2.4. In the preliminary analysis (Theil-Sen test) carried out for this work, statistically significant evidence ($p < 0.05$) of an increase of 0.39 ppb per year was found during the period 2010-2022 in the stations located within Mexico City. This implies an increase of ~5 ppb in 12 years. Although the number of activations of Phase 1 Environmental Contingencies due to O_3 has not increased, nor has a decrease been observed in the number of days exceeding the limit values of the NOM-020-SSA1-2021 standard for health protection. If this trend continues, the number of days that exceed the limit values of the standard could increase in the coming years. This situation could be aggravated by the gradual reductions in the maximum O_3 limits provided by the standard for the following years. In ProAire 2021-2030 of the MCMA, the observed trend is discussed, attributing the increase in O_3 levels to changes in atmospheric chemistry caused by the differential decrease in NO_X and volatile organic compounds (VOCs) emissions, as well as changes in regional or global meteorology. (SEDEMA et al., 2021). However, the scientific community has not yet addressed the issue; it is important to investigate the causes and impacts (Velasco & Retama, 2017). The ProAire indicates that reductions of 50% and 71% in all sources that emit O_3 precursors would be necessary to reach O_3 concentrations of 90 ppb for the 1-hour average and of 51 ppb for the 8-hour moving average, respectively.

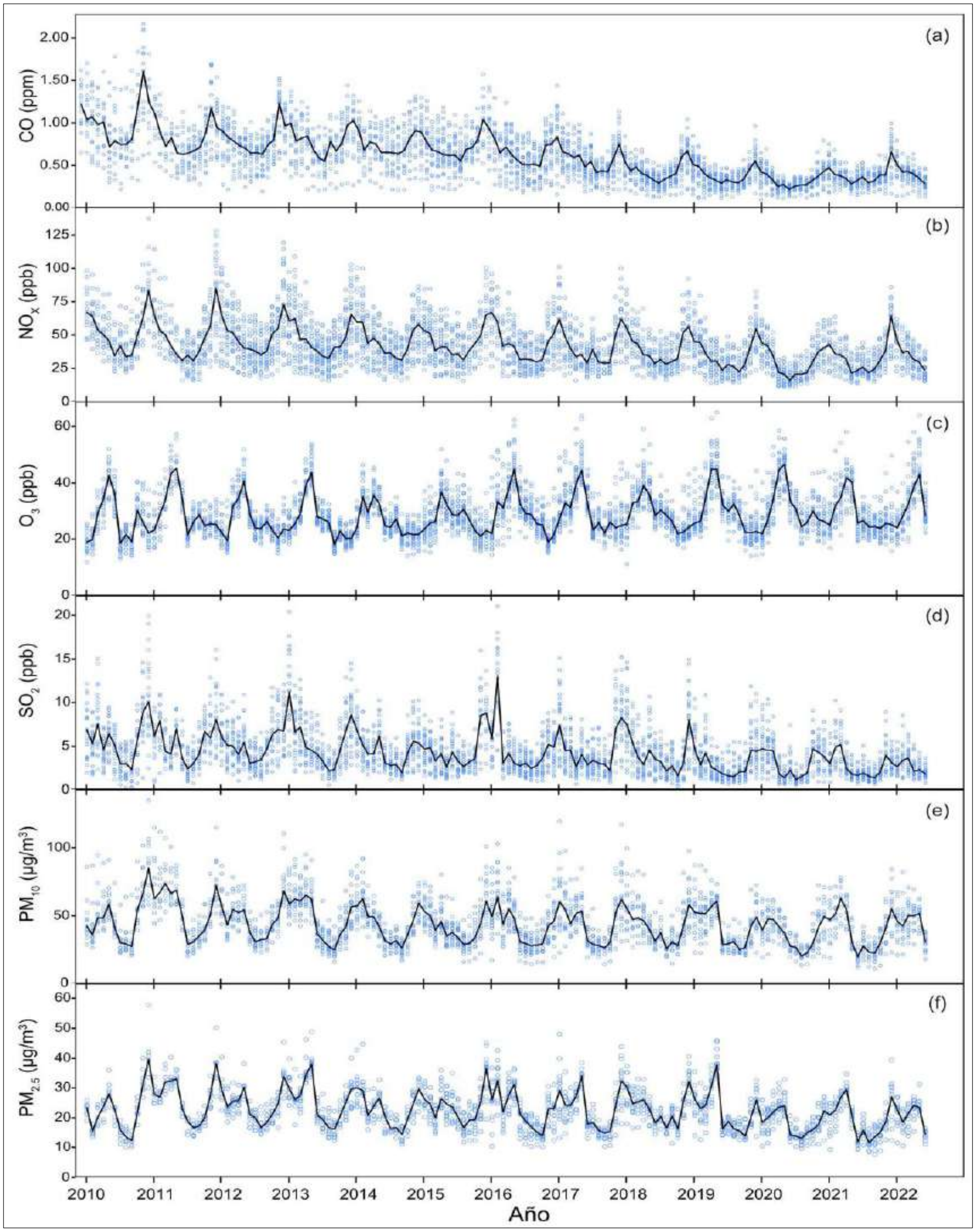


Figure 2.2. Time series of the monthly averages of (a) CO, (b) NO$_X$, (c) O$_3$, (d) SO$_2$, (e) PM$_{10}$ and (f) PM$_{2.5}$ in the MCMA. The circles indicate the average value in each of the monitoring stations of the Automatic Atmospheric Monitoring Network (RAMA), the black line indicates the median value for monthly values. In the construction of the graph, the months with 75% or more of valid data were used. (Own elaboration with data from the Air Quality Monitoring Directorate, www.aire.sedema.cdmx.gob).

From the review of the objectives set out in the ProAire 2021-2030, there was an ambiguity in the reduction goals by not clearly specifying the values to be achieved, as well as the monitoring and evaluation metrics. For example, *Specific Objective 1* (*Reduce emissions from priority polluting sources and categories*) proposes strategies to reduce emissions of O_3 precursor pollutants and secondary particles, but does not indicate the concentrations that are expected to be achieved; in addition, it does not specify the expected environmental benefits. Another example, *Specific Objective 2 (Reduce the concentrations of particles and O_3)* proposes to reduce the maximum concentrations of O_3 and the average concentration of PM_{10} and $PM_{2.5}$ particles before 2030, but does not indicate the target value or the expected reduction rates.

Regarding particle pollution, the concentrations of PM_{10} (Figure 2.2e) maintain a decreasing trend, except in the stations located in the northeast of the metropolitan area, where increases in concentrations were observed in 2021 and 2022, possibly as a consequence of urban development in the region. Regarding $PM_{2.5}$, the average concentrations observed before the COVID-19 pandemic did not show changes in their trend during the previous decade (Figure 2.2f); however, in 2021 and 2022, there was a decrease, possibly due to the difficulty of access to monitoring equipment at the sites located in hospitals and health centers, some of which consistently registered the highest concentrations (for example, Xalostoc).

The ambient concentrations of CO and SO_2 decreased considerably and remain below the limit values of the corresponding health protection standards. Occasionally, there are short-term increases in SO_2 concentrations due to the presence of pollution plumes of regional origin. The concentrations of these pollutants in ambient air are so low that they are in the lower region of the analyzers' measurement scale, close to their detection limit, where quantification is less sensitive and uncertainty is greater. To increase the precision and accuracy of the measurements, it is necessary to move towards technologies with higher sensitivity. Recently, through the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis (*Programa de Fortalecimiento de las Capacidades de Monitoreo de la Calidad del Aire en la Megalópolis*, hereinafter Reinforcement Program, see Section 2.4), the DMCA received five devices for measuring trace levels of SO_2 and four for the measurement of CO. It is important to mention that SO_2 and CO monitoring is conducted in 32 and 31 of the RAMA stations, respectively. The field deployment of these new instruments will require adaptations in the monitoring sites and calibration methodologies.

In the case of NO_2, it is known that the chemiluminescence method currently used overestimates the concentration due to the presence of common interfering compounds in urban air. Various nitrogenous species - including nitric acid (HNO_3), nitrous acid (HNO_2) and some organic and inorganic nitrates - are reduced within the instrument's catalytic converter and induce a positive response that adds to the NO_2 response. Therefore, current monitors also overestimate NO_X measurements (obtained from the sum of NO_2 and NO concentrations), which is why members of the scientific community suggest referring to them as NO_Y instead of NO_X. In observations made at the Merced monitoring station in 2003, an overestimation of 22% was identified in the NO_2 concentration reported by RAMA (Dunlea et al., 2007), while more recent measurements made at the Environmental Analysis Laboratory in the northern part of the city, showed overestimations of 17% and 8% during the day and at night, respectively (Zavala et al., 2020). Because NO_2 has adverse effects on health, considering the recent changes in the limit values of NOM-023-SSA1-

2021 and taking into account that it is an important O_3 precursor, efforts should be made to improve its measurement using methods suitable for the conditions of Mexico City. Since 2016, the DMCA has evaluated the response of Cavity Attenuated Phase Shift (CAPS) monitors for NO_2 measurement. These monitors measure NO_2 absorption at 450 nm without converting NO_2 to another species, and therefore do not suffer from interference from other nitrogenous species as standard chemiluminescence-based monitors do. NO_2 measurement is currently carried out in 32 monitoring stations. In 2018, the network received four CAPS analyzers through the Reinforcement Program.

2.1.3. Effects of air pollution on the composition and acidity of rainwater

The Atmospheric Deposition Network (REDDA) is part of SIMAT and operates with the support of the Institute of Atmosphere Sciences and Climate Change (ICAyCC) at UNAM. REDDA is unique in the country and maintains permanent monitoring of the composition of the atmospheric wet deposition (mainly rainwater) through the collection of weekly samples. Among the most important effects of air pollution on rainfall are changes in acidity and in its ionic composition. The presence of acid rain is a common phenomenon in Mexico City, the highest acidity ($pH < 4.5$) has been reported in the sampling sites located in the south of the city, precisely in the areas where the remnants of the original forest that covered most of the mountains that surround the basin are found and in the areas with the highest agricultural activity in the entity (SEDEMA, 2020). The median value for the weighted pH during the period 2003-2018 was 5.3, which is lower than the value of 5.6 considered as the natural pH value in rainwater. In the last decade, pH values of up to 3.8 have been recorded (Sosa-Echeverría et al., 2022).

The composition of the precipitation is dominated by ammonium (NH_4^+), sulfate (SO_4^{2-}), nitrate (NO_3^-), and bicarbonate (HCO_3^-) ions. Their sum contributes ~75% of the total ionic composition. The presence of $SO_4^{2-}$and nitrate NO_3^- is related to the incorporation or formation of species produced by the oxidation of SO_2 and NO_X during the formation of raindrops or by the incorporation of atmospheric aerosols into the aqueous phase.

It has been observed that the sampling sites located in the north generally exhibit the highest concentrations of SO_4^{2-}, NH_4^+ and calcium (Ca^{2+}) ions, while the sites located in the south of the city report the highest levels of acidity, suggesting that the urban characteristics and the distribution of air pollutants have an impact on the composition of rainwater.

Despite the low levels of SO_2 in ambient air, SO_4^{2-} is the most abundant ionic species in rainwater after NH_4^+ (Sosa-Echeverría et al., 2022). The NH_4^+ is mainly responsible for the neutralization of the acidic species, followed by the Ca^{2+} ion. It is known that NH_4^+ originated from gaseous NH_3, which is emitted primarily from agricultural activity and some urban sources including: exhaust emissions from vehicles with catalytic converters, water treatment, sewers, and garbage dumps. According to previous (Moya et al., 2004; San Martini et al., 2005) and recent (Retama & Velasco, 2022) results, NH_3 is an abundant species in the atmosphere and its main sources and contributions are not fully identified.

The effects of rainwater acidity on ecosystems, urban infrastructure, crops, and architectural heritage have been widely studied in other regions of the world (for example, Grennfelt et al., 2020; Livingston, 2016; Liu et al., 2019). However, in Mexico City, little is known about its impacts. The problem of acid rain and its effects are topics that are relegated from environmental management and outside of the SIMAT coverage area.

2.1.4. Influence of meteorology on air pollution

The Meteorology and Solar Radiation Network (REDMET, *Red de Meteorología y Radiación Solar*), which is part of SIMAT, maintains a permanent monitoring of the meteorology at the ambient and vertical level, and makes it possible to establish relationships between local meteorological conditions and air quality.

The basin of Mexico is partially confined by mountain ranges to the west, south, and east, with a wide opening to the northeast, between the Sierras de Guadalupe and Nevada. The natural depressions that form between the Ajusco-Chichinautzin and Nevada mountain ranges, to the southeast, and between the Guadalupe and Las Cruces mountain ranges, provide openings that allow ventilation of the basin. The air currents generated there present a higher wind speed and little variation in its direction (see Figure 2.3).

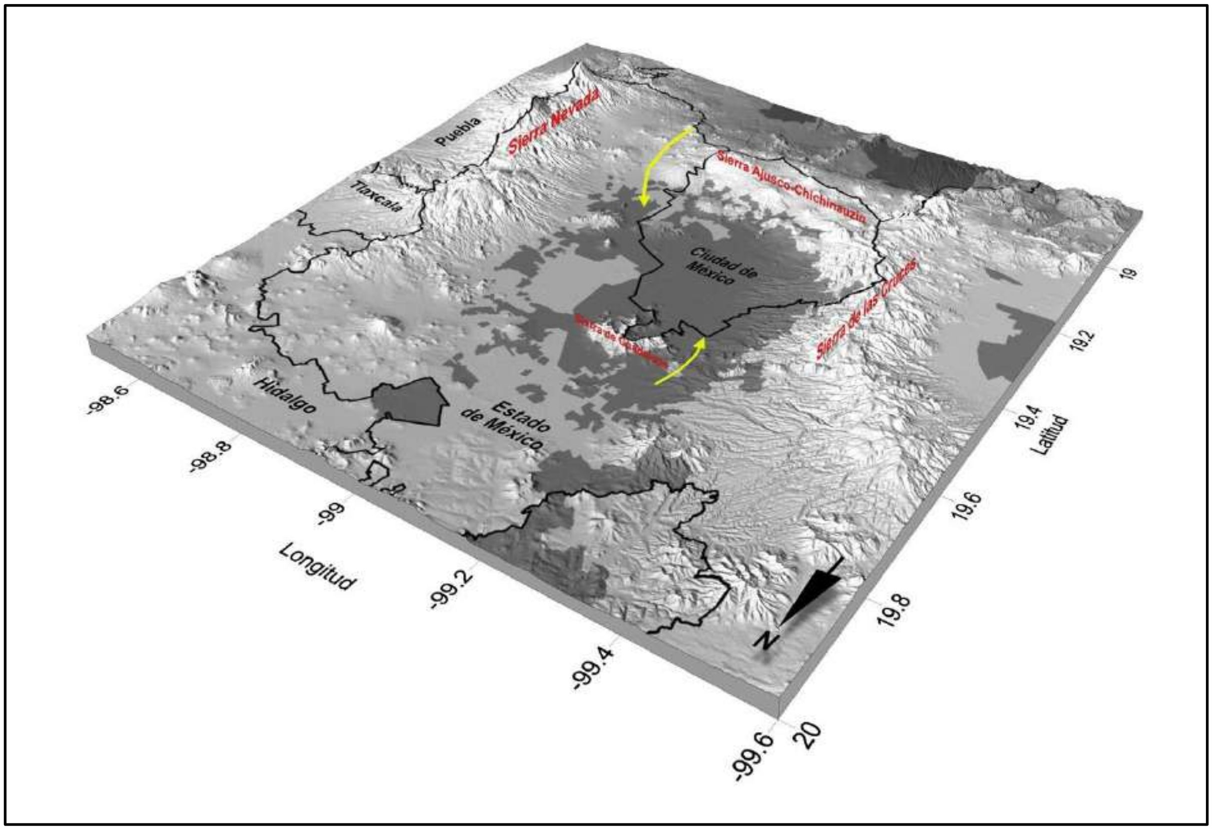


Figure 2.3. Relief of the basin of Mexico seen from the northwest. In the figure the mountain ranges that surround it are indicated, the yellow arrows indicate the channeled wind flows to the northwest and southwest. The areas shaded in dark gray correspond to urbanized areas, the black line indicates the political limits of the states. (Own elaboration).

Wind patterns determine the fate of pollutants. In the early hours of the day, the katabatic flows concentrate the air masses over the central portion of Mexico City, generating a region of atmospheric stagnation. During this period, pollutants emitted in the early hours of the day are gradually concentrated within the narrow nocturnal boundary layer with little vertical and horizontal mobility. The concentrations of primary pollutants, intensely emitted when the city wakes up and economic activities begin, reach their maximum concentrations. The presence of thermal inversions tends to extend the persistence of stagnation episodes, mainly during winter. At dawn, the thermal flows, coming from the north of the central plateau, dominate the movement of the air masses. These are strengthened by the warming of the mountain slopes, generating a superficial current in a southwesterly direction, and an active transport of accumulated pollutants is observed in the center of the city and north of the altiplano. In this period, the pollutants undergo a rapid dilution due to the growth in the height of the boundary layer, in addition to a progressive chemical transformation caused by the intense solar radiation characteristic of the altitude and latitude of the basin.

While the concentrations of primary pollutants decrease during the course of the morning, the presence of secondary pollutants such as O_3 and secondary organic aerosols (SOA) increases. During the afternoon, the channeled flow from the southeast strengthens and, occasionally, regional flows coming from the south of the entity favor the formation of convergence areas over Mexico City, generating areas with stability where the wind speed (vertical and horizontal) decreases, allowing the accumulation and stagnation of pollution. These areas appear more frequently in the south and the center of the city, they can remain for minutes to hours, and disappear with an increase in wind speed. The air masses entrained by the channeled flow can be enriched with O_3 and other pollutants (García-Yee et al., 2018). The concentration of pollutants and the intense chemical transformation in these convergence zones usually cause significant increases in O_3 concentrations, which can reach sufficient levels for the activation of the Program to Prevent and Respond to Atmospheric Environmental Contingencies (PPRECAA, *Programa para Prevenir y Responder a Contingencias Ambientales Atmosféricas*) in one or several monitoring stations (see Section 6.4.4 in Chapter 6 for a description of PPRECCA). The location, spatial extent, and duration of these convergence zones may vary depending on surface and upper wind characteristics, boundary layer properties, and the presence of synoptic-scale systems. Figure 2.4 schematically shows the behavior of the winds in the basin. The meteorology related to O_3 pollution is extensively described in de Foy et al. (2005, 2008) and Fast & Zhong (1998). Salcido et al. (2019) present a detailed analysis of the relationship between surface wind and pollutant fluxes in Mexico City.

Surface meteorological measurements provide information on the local behavior of winds and pollution variability, however, observations at different heights are required to understand atmospheric dynamics and their effects on pollution, as previous studies have shown (Doran et al., 2007; Molina et al., 2007). In this sense, the DMCA maintains a permanent monitoring of meteorological conditions within the planetary boundary layer and in upper layers using instruments for measuring the vertical profile. Unfortunately, the operation of these instruments requires specialized personnel and additional economic resources.

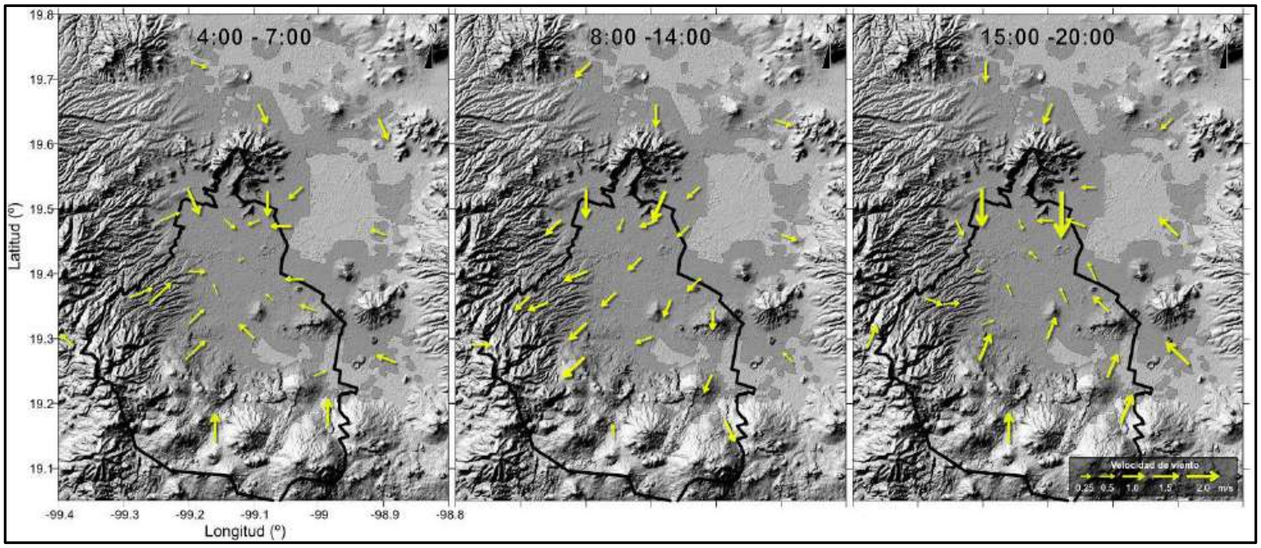


Figure 2.4. Typical wind field patterns during the dry-hot season (Mar-May) for the periods (a) 4:00 a.m. to 7:00 a.m., (b) 8:00 a.m. to 2:00 p.m. and (c) 3:00 p.m. to 8:00 p.m. The size of the vectors indicates the average wind speed and they were estimated using data from the Meteorology and Solar Radiation Network (REDMET) for the years 2019 to 2021. (Own elaboration with data from Air Quality Monitoring Directorate, www.aire.cdmx.gob.mx).

During the dry months of the year (Nov-May), forest and agricultural fires in the central and southern states of the country are frequent and represent an important source of atmospheric pollutants (Ríos & Raga, 2018). Under certain meteorological conditions, fires that occur in forests, grasslands, or agricultural areas surrounding the MCMA can rapidly increase the levels of fine particle. Also, large fires that occur in the most remote entities (such as Michoacán or Guerrero) are an additional source of pollutants for the city (Carabali et al., 2021) whose impact will depend on the direction and intensity of wind flows at meso and synoptic scales. The impact of the regional transport of the emissions produced by the fires represents a challenge for air quality management, mainly during the activation of the PPRECAA.

On the other hand, the city is experiencing an increase in temperature whose origin and consequences have not yet been thoroughly addressed by science. This topic is discussed in more detail in Chapter 4 of this document.

2.2. Monitoring of air quality in the rest of the entities of the Megalopolis

Monitoring activities in the entities that surround Mexico City are concentrated in the capital cities and the main urban settlements. Figure 2.5 shows the distribution of the monitoring stations located in the entities that are part of the Megalopolis: Querétaro, Hidalgo, Tlaxcala, Puebla, Morelos, State of Mexico, and Mexico City. Only the automatic stations (continuous monitoring stations) are referred to in this section because of their ability to provide data with a higher temporal resolution on air quality. On the website of the National Air Quality Information System (SINAICA, *Sistema Nacional de Información de Calidad del Aire*. https://sinaica.inecc.gob.mx) and the National Air Quality Reports published by INECC, it is possible to find detailed information on the location of the stations, data availability and updated air quality situation. The purpose of this section is to present a general overview of the air quality and monitoring situation in the region based on the available information. In order to evaluate the current pollution situation, a basic analysis of the hourly data was carried out using the validated databases available at SINAICA; the results are described below for each entity.

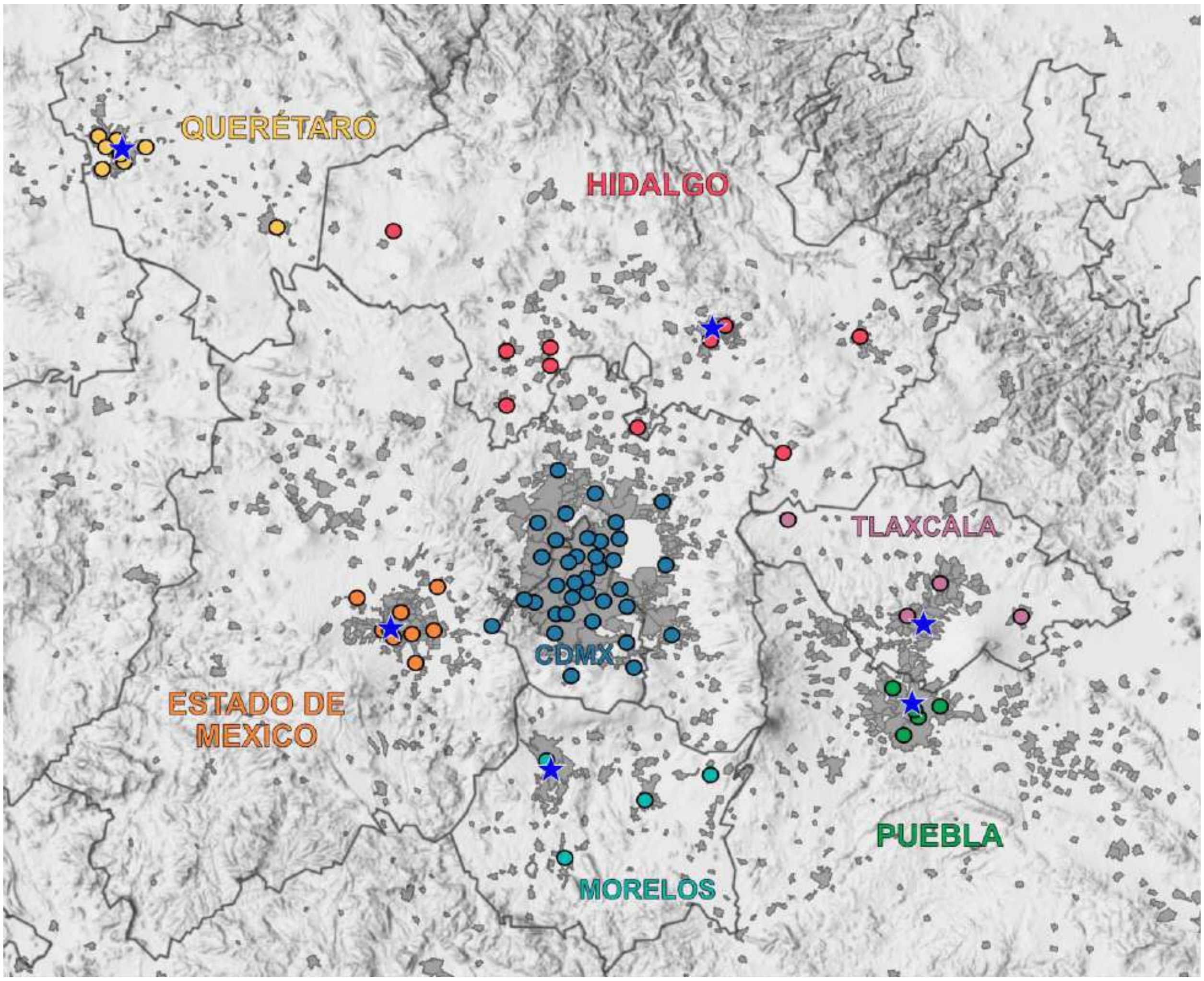


Figure 2.5. Stations for continuous monitoring of criteria pollutants in the states that make up the Megalopolis. The sites that are managed by each entity are distinguished by color; only the stations that were registered with SINAICA in 2022 are shown. The capital of each state is indicated with a blue star. (Own elaboration with data from INEGI (2017) and SINAICA (INECC, s.f.), accessed on July 25, 2022).

2.2.1. State of Mexico

The State of Mexico has two important urban conglomerates, the metropolitan area of the Toluca Valley (ZMVT, *zona metropolitana del Valle de Toluca*) and what is known as the Cuautitlán-Texcoco metropolitan area (Government of State of Mexico, 2018). Both have automatic networks for continuous monitoring of criteria pollutants. The network in the metropolitan area of Toluca Valley is operated by the government of the State of Mexico, while the network installed in the Cuautitlán-Texcoco metropolitan area is part of SIMAT. According to SINAICA, in July 2022 the ZMVT had nine continuous monitoring stations: Calimaya, Ceboruco, Centro, Oxtotitlán, San Cristóbal, Metepec, Almoloya de Juárez, San Mateo Atenco and Xonacatlán (see Figure 2.6). The official site of the Air Quality Network of the metropolitan area of Toluca Valley (https://rama.edomex.gob.mx/calidaddelaire) displays a larger number of stations for reporting the local air quality index, but only those described above report to SINAICA and are included in the periodic reports of the local authority.

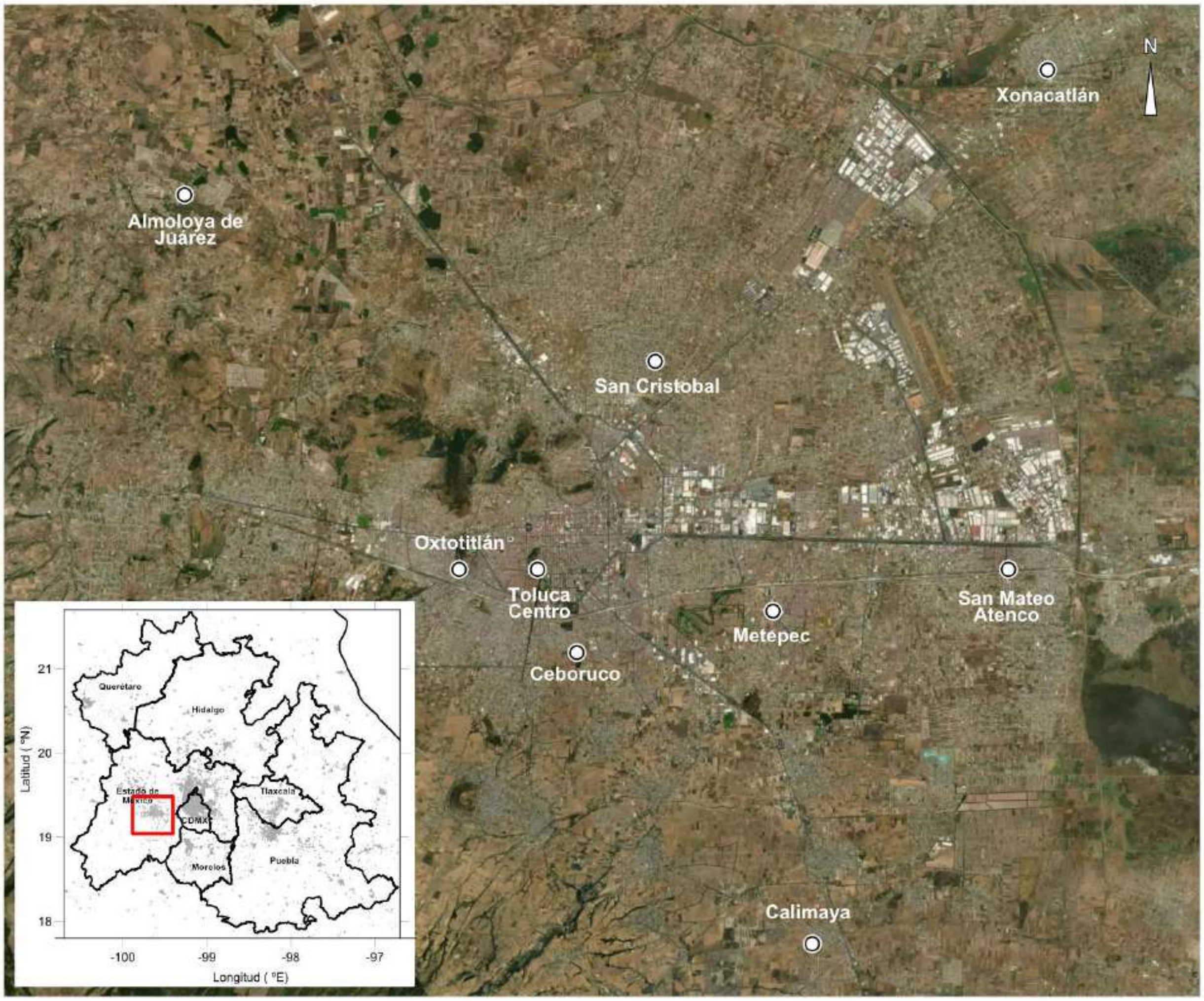


Figure 2.6. Location of the continuous monitoring stations in the metropolitan area of Toluca Valley, State of Mexico. Map updated to July 2022. (Own elaboration with data from SINAICA, accessed on July 25, 2022; image: Google Earth).

Toluca de Lerdo is a city that sits at an altitude of 2,660 masl in a valley surrounded by mountains where physiography has important influence on local meteorology and, therefore, is a determining factor in the behavior of the air quality. The urbanization extends along an east-west axis, with an important industrial corridor located to the northeast. The configuration of the monitoring network corresponds to the urban distribution, within the urban core there are six stations, the remaining three are located in population centers close to the city: Calimaya in the south, Almoloya de Juárez in the northwest, and Xonacatlán in the northeast.

The pollutants PM_{10}, $PM_{2.5}$ and O_3 are mainly responsible for the deterioration of air quality in the ZMVT; their concentrations frequently exceed the limit values of the air quality standards for health protection. According to the national air quality report for 2019 (INECC, 2020), at least one environmental health standard was not met in the ZMVT on 231 days, which is equivalent to 63% of the days of the year. The frequency with which one of the limit values established by the regulations for PM_{10}, O_3 and $PM_{2.5}$ was exceeded was 52%, 32% and 24%, respectively. According to the local air quality improvement program (ProAire 2018-2030) (Gobierno del Estado de México, 2018), pollution levels at ZMVT stations are usually higher than in the stations located in the valley of Mexico, except for O_3.

Rainfall determines the seasonality of air pollution in the ZMVT during the year. The lowest concentrations are recorded during the rainy months (June to September). The highest levels of particles are generally observed between December and May, while those of O_3 between March and May. The time series in Annex B show the trend of daily averages for criteria pollutants between 2016 and 2020.

As can be seen in Figure 2.7, gaseous pollutants show a downward trend, except for O_3, which has shown an increasing trend in recent years. In the case of PM_{10} and $PM_{2.5}$, no important changes are observed.

According to the ProAire 2018-2030, the technical audits carried out on the local air quality monitoring system show a gradual improvement in its operation and maintenance. However, the monitoring network suffers from budgetary limitations that prevent it from guaranteeing full compliance in all monitoring activities. Previous audits have also recommended reviewing the spatial representativeness of the monitoring sites. The renovation and new equipment provided by the Reinforcement Program made it possible to partially address some of the network shortcomings. through.

The air quality situation in the Cuautitlán-Texcoco metropolitan area was previously discussed in the description of air quality in the MCMA (Section 2.1).

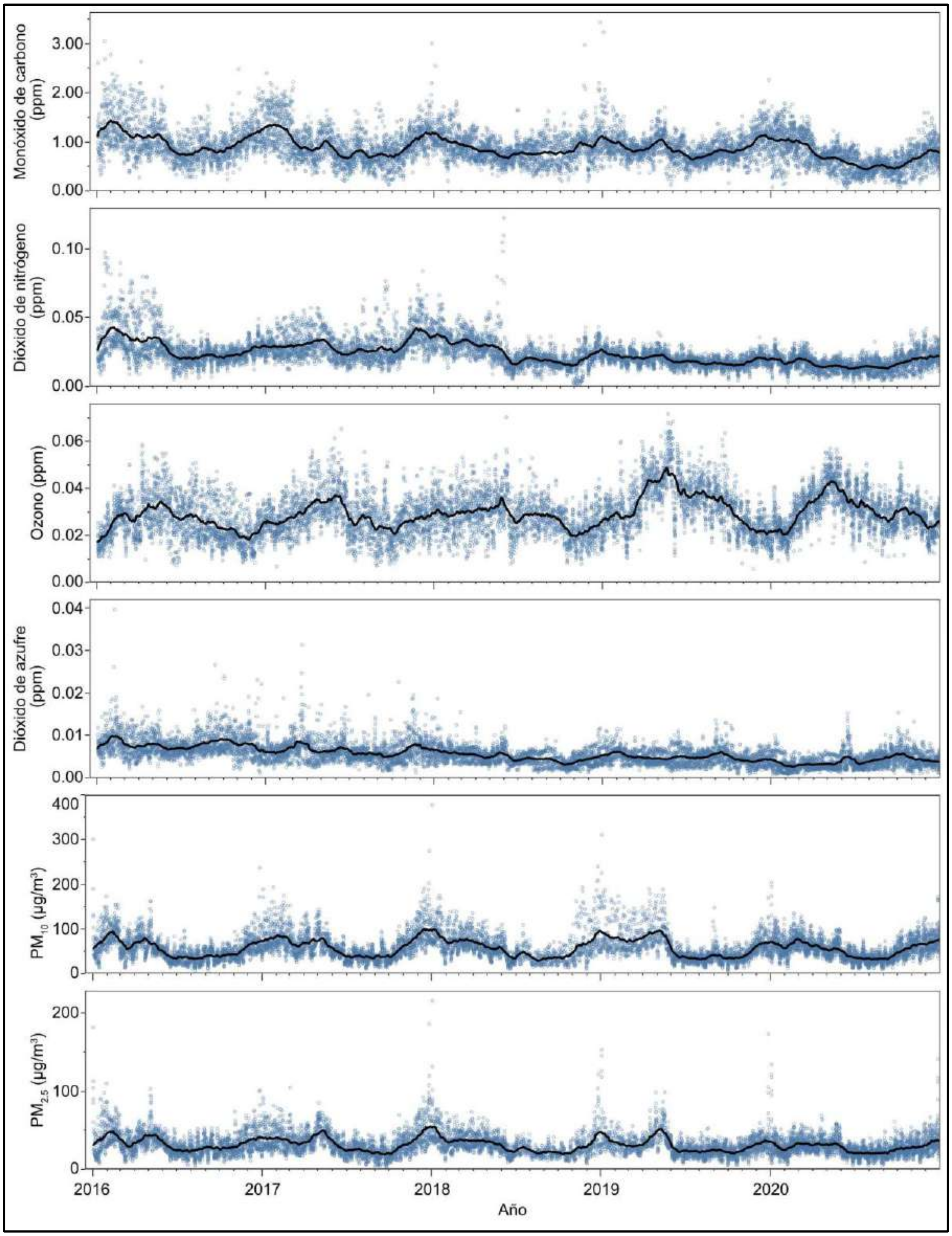


Figure 2.7. Time series of the daily averages of the criteria pollutants in the stations of the metropolitan area of Toluca Valley. The circles correspond to the daily averages reported in the different monitoring stations, the solid black line indicates the 30-day moving average of all the stations. (Own elaboration with data from SINAICA, accessed on July 25, 2022).

2.2.2. Hidalgo

The air quality monitoring network of the state of Hidalgo covers an important part of the Hidalgo highlands in the south of the state, including monitoring sites in the Mezquital Valley, the Comarca Minera, the Tulancingo Valley, the basin of Mexico and the Pulquera Plateau. In the highlands of Hidalgo is the capital city, Pachuca de Soto, and the main urban and industrial settlements of the entity. For environmental management purposes, the region is organized into three atmospheric basins: Tula, Pachuca, and Tulancingo. These basins were delimited according to population density, extent of urban settlements, industrial activity, geographical configuration, meteorology and climate.

Pachuca and Tulancingo are the most important cities in the state, the fist has two monitoring stations while the second has one. According to INECC, as of July 2022, stations were operating in the urban centers of the municipalities of Tula de Allende, Atitalaquia, Atotonilco, Tepeji del Río, Tizayuca, Tepeapulco and Huichapan. Despite the fact that there are some manual monitoring stations, the mountainous area, which covers most of the state's territory, is underrepresented by monitoring. The location of each of the monitoring stations can be seen in greater details in Figure 2.8.

The dry climate dominates an important portion of the Mezquital Valley and the Comarca Minera, which is why dust storms are frequent during the dry season. There are important agricultural areas dominated by irrigated cultivation, during preparations for sowing and treatment of crop residues these areas usually become an important source of dust. The presence of intense winds coming from the north is frequent in Comarca Minera, mainly between the months of June and October, which usually causes dust storms in the region; in fact, the city of Pachuca is known as Bella Airosa for this reason. Despite this, the local inventory of emissions of pollutants does not reflect a significant contribution of suspended particles from agricultural and natural sources to pollution (Gobierno del Estado de Hidalgo, 2016). On the other hand, there is intense urban growth to the south of the entity and additional impacts on air quality due to urbanization and housing construction activities in several municipalities have not been ruled out.

The southern part of the state of Hidalgo borders the State of Mexico and is located near Mexico City, hence they share the same air masses in the region. During most of the year it is common to observe wind flows coming from the north of the plateau, which transport air masses towards Mexico City during the mornings. The frequent detection of increases in SO_2 at the monitoring stations in Mexico City is related to the transport of emissions generated from the Tula-Tepeji region, where a refinery, a thermoelectric plant, and several cement factories are located (de Foy et al., 2009; Gobierno del Estado de Hidalgo, 2016; SEDEMA, 2018).

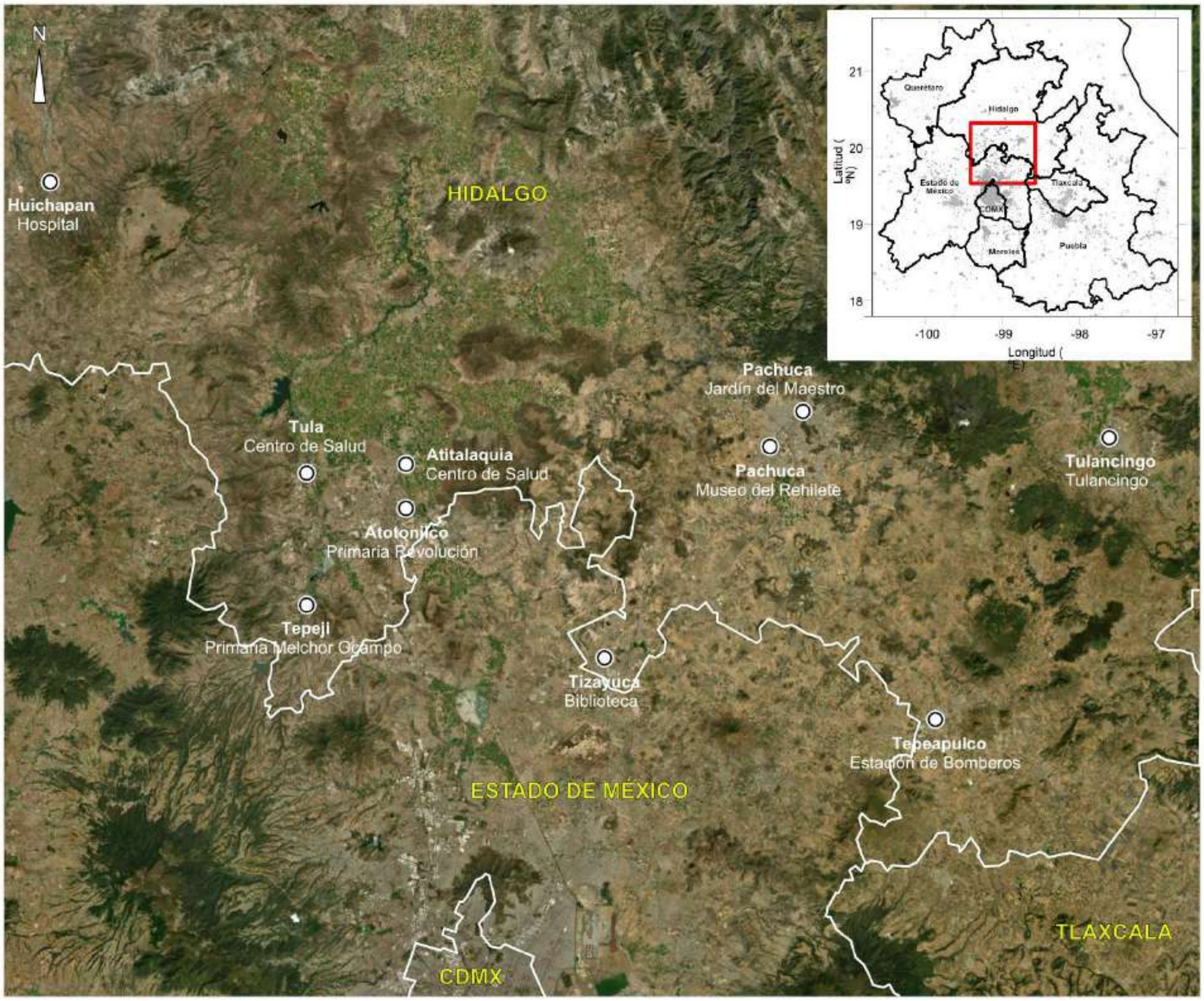


Figure 2.8. Location of continuous monitoring stations in the state of Hidalgo. The stations are indicated according to the municipality in which they are located and the name assigned to each one by the local environmental authorities. Map updated to July 2022. (Own elaboration with data from SINAICA, accessed on July 25, 2022; image: Google Earth).

According to the 2019 National Air Quality Report (INECC, 2020), this year the limit value of at least one criteria pollutant was exceeded in most of the different urban settlements, except in the city of Tula where it was not exceeded. In Atitalaquia, at least one air quality standard exceeded in 33% of the days of the year, 29% in Atotonilco, 16% in Pachuca and Tizayuca, 15% in Tepeji del Río, 12% in Tepeapulco, 6% in Huichapan and 4% in Tulancingo. In Pachuca, Tulancingo, Huichapan and Tepeji del Río, the pollutant that most frequently failed to comply with the standard was O_3. While in Tizayuca, Atitalaquia, Atotonilco and Tepeapulco. it was the suspended particles, mainly PM_{10}. It is baffling that Tula -one of the cities with the highest discharge of pollutants into the atmosphere- complies with ambient air quality levels in accordance with current regulations.

The importance of the Tula-Tepeji industrial corridor as a source of air pollutants at local and regional scales is a constant topic of discussion between the scientific community and those responsible for environmental management (de Foy et al., 2009; Rivera et al., 2009; Almanza et al., 2012; Melgar-Paniagua, 2013; García-Escalante, 2014; Vega et al., 2021; ICM, 2021; MCE2-INE, 2009). According to the document "Air Quality in the Tula Atmospheric Basin" (*Calidad del Aire en la Cuenca Atmosférica de Tula,* SEMARNAT, 2020), the basin is made up of 12 municipalities and is home to 58 local and federal companies. It is the headquarters of a refinery, two electricity generation plants (one conventional thermoelectric and one natural gas combined cycle), six cement plants, four lime kilns, metal-mechanic and chemical industries, among others. According to public opinion, this region is identified as one of the most contaminated areas in the country (Monroy, 2019; EFE, 2020). However, the results of ambient air quality monitoring does not seem to reflect the true magnitude of the problem. The data show levels of pollutants similar to those reported in other urban areas of the Megalopolis. In 2022, an intensive air quality monitoring campaign was carried out in the region, financed with resources administered by CAMe (INECC, 2022). The results will be important to objectively identify the magnitude of the problem, but also so that the authorities responsible for monitoring can assess the capacity of their network to characterize the problem of deteriorating air quality in the state of Hidalgo. See Section 4.3.4.1 in Chapter 4 for more information about the air quality in the Tula-Tepeji Industrial Complex.

As can be seen in the figures in Annex B, the concentrations of O_3, $PM_{2.5}$ and PM_{10} present a clear seasonality, with maximums for O_3 between April and May, while for suspended particles the maximums usually occur during most of the dry season (Nov-May).

During the review of the databases, indications of possible operational problems in the atmospheric monitoring were found. For example, in the case of CO, as shown in Figure 2.9, various monitoring sites present ascending trends that abruptly fall after a period of time. This anomalous behavior suggests possible problems with the stability of the instrument's baseline or deficiencies in the measurement quality assurance. These problems were apparently not identified during the data review and validation processes by the technicians from the same network and those from INECC who manage SINAICA. The presence of data with potential errors and quality deficiencies was identified for all pollutants, but were evident for those pollutants with concentrations close to the detection limit of the instruments. Obviously, data with errors of this type may not be useful for air quality management needs.

The evaluations carried out by INECC showed signs of operational problems in the atmospheric monitoring network of the State of Hidalgo (INECC, 2016a,b), which were even mentioned in the ProAire 2016-2024 of the entity (Gobierno del Estado de Hidalgo, 2016) and the ProAire of the Megalopolis (SEMARNAT, 2017); however, the problems persist. They highlighted the lack of spare parts and consumables for the operation and maintenance of the equipment, and the need to update some instruments that are at the end of their useful life. It was also recommended to relocate some monitoring stations to more representative sites. Some of these aspects were recently addressed through the Reinforcement Program, with the supply of 17 pieces of equipment and spare parts for network maintenance.

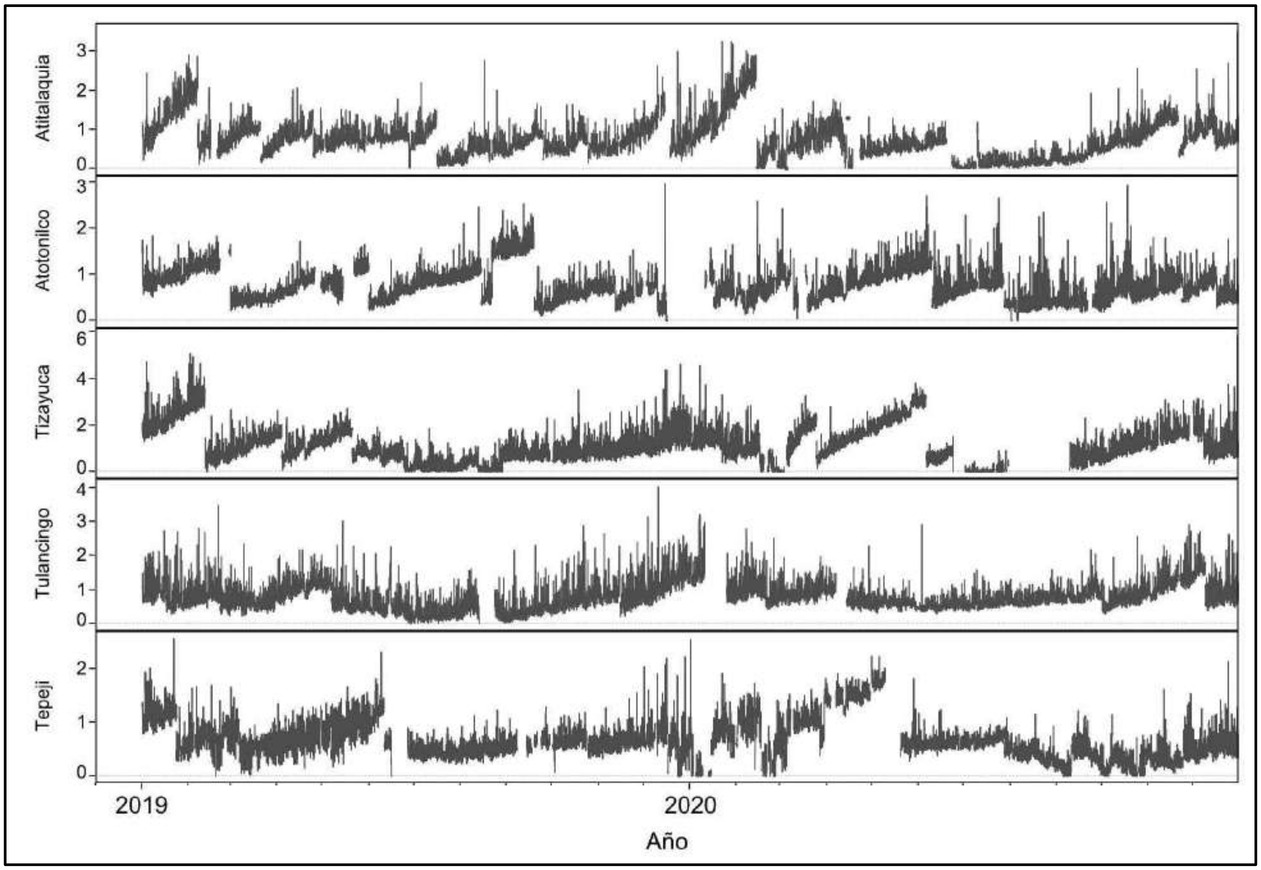


Figure 2.9. Time series of the hourly averages of CO in some of the air quality monitoring sites in the state of Hidalgo for the period 2019-2020. In all the sites, there are upward trends that abruptly fall after a period of time. This anomalous behavior suggests problems in the operation and maintenance of the monitors. Concentrations are in units of parts per million (ppm). (Own elaboration with data from SINAICA, accessed on July 25, 2022).

2.2.3. Morelos

The state of Morelos is located in the southern portion of the Megalopolis, it is characterized by a complex topography due to the interaction between the Eje Neovolcánico, the mountain range south of Puebla and the Sierra Madre del Sur. It has a warm climate with a rainy season between June and September, reaching an average annual rainfall of 1045 mm. Most of the territory corresponds to non-forestry land, where agricultural activity covers 36.7% of the surface of the state. Urban settlements cover 4.5% of the territory. The two main urban areas are Cuernavaca and Cuautla.

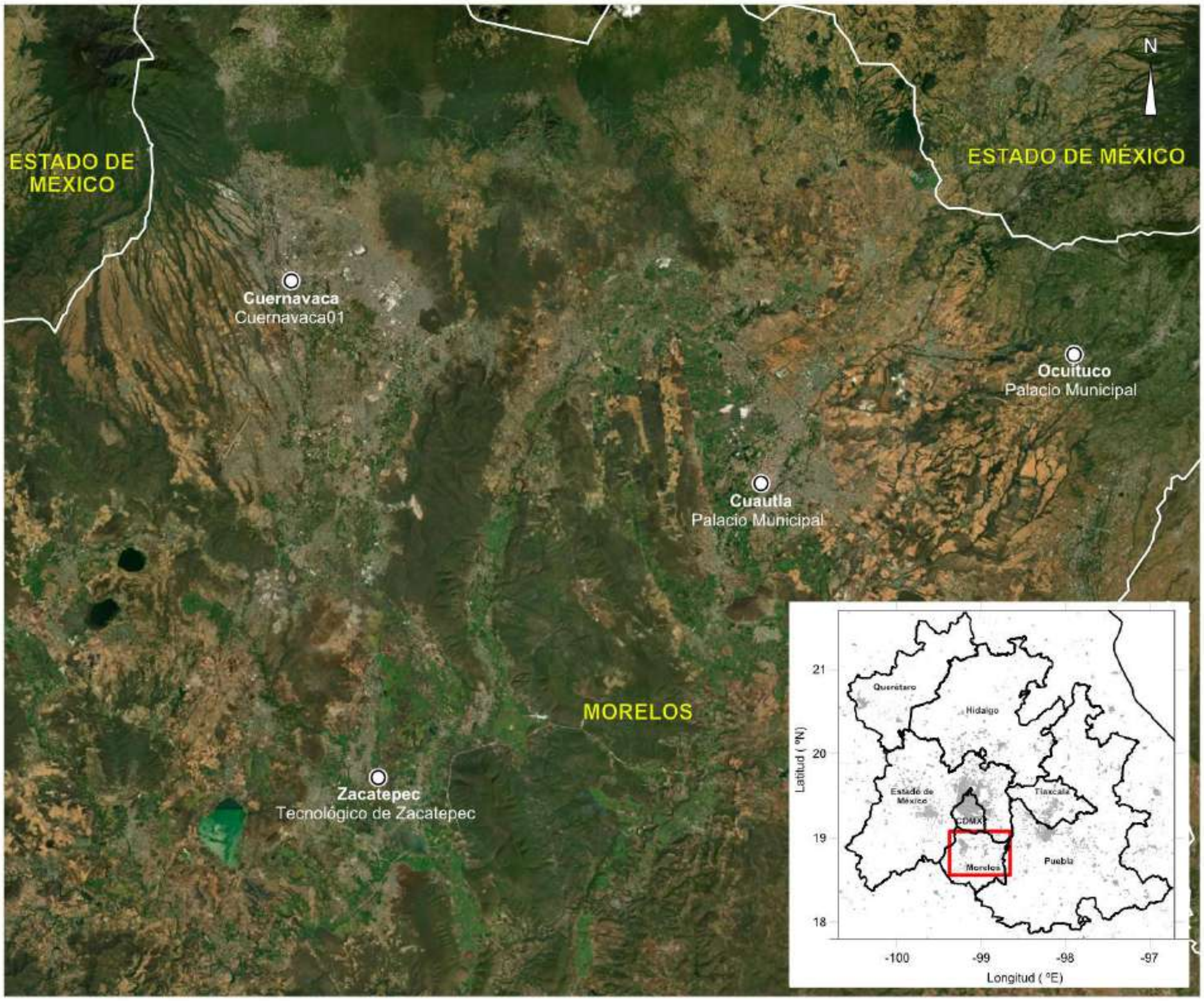


Figure 2.10. Location of the continuous monitoring stations in the state of Morelos. The stations are indicated according to the municipality in which they are located and the name assigned to each one by the local environmental authorities. The first line on the label indicates the municipality, the second line the name of the station. Map updated to July 2022. (Own elaboration with data from SINAICA, accessed July 25, 2022; image: Google Earth).

Air quality monitoring in Morelos has been carried out intermittently since 2000. The entity has four monitoring stations, two of them are located in the cities of Cuernavaca and Cuautla. The Ocuituco station is aimed at monitoring the emissions associated with the activity of the Popocatépetl volcano, while the Zacatepec station is aimed at evaluating the impact of emissions produced in the sugar industry. The location of the monitoring stations is presented in Figure 2.10.

The complex topography in the west of the entity presents challenges for atmospheric monitoring due to the influence on meteorology and the movement of air masses. Additionally, the region is exposed to the influence of regional transport of pollution generated in Toluca and the MCMA. Salcedo et al. (2012) carried out two monitoring campaigns in March 2007 and March 2009 with the objective of making a preliminary diagnosis of air quality in various locations in Morelos, as well as to understand the processes responsible for the O_3 pollution observed in the entity. The findings of this study provided a useful description of the overall air quality situation in the region, and presented the challenges and opportunities for monitoring, improving emissions inventories and research needs. Although this study was carried out more than a decade ago, its results and recommendations remain valid. Regarding air quality monitoring, the study pointed out the following:

- The urgency of establishing a functional air quality monitoring network in the state capable of generating reliable data to identify trends and variability of pollutants and their relationship with meteorological processes.
- The need to expand the monitoring network to other urban settlements with high population density, such as Xochitepec, Temixco, Jiutepec and Yautepec, and those located between Cuernavaca and Cuautla.
- The lack of monitoring sites in rural and agricultural areas to determine ozone impacts on vegetation.
- Lack of information on the abundance and physicochemical properties of atmospheric particles in the entity.

One of the most important deficiencies of the Morelos monitoring network is the low data capture. With the exception of the station located in Cuernavaca, the rest present a significant absence of data between 2016 and 2019. The corresponding graphs in Annex B show the time series with the daily averages and the frequent absence of data is notable. Although it is not the purpose of this document to evaluate the data, it is important to mention that during the review, indications of possible deficiencies in its quality were observed, for example, drifts in the baseline, calibration problems, insufficient review and validation, among others.

According to the 2019 National Air Quality Report (INECC, 2020), that year the limit values of the NOM for O_3, PM_{10} and $PM_{2.5}$ were exceeded in various monitoring stations of the entity. According to the data, the number of days with unfavorable air quality increased in Cuernavaca, Zacatepec and Ocuituco, compared to 2018. Cuernavaca went from 15 to 43 days, while Zacatepec went from 54 to 64 days and Ocuituco from 19 to 64 days. According to the environmental authorities, this increase was due to greater data capture due to the installation of new monitoring equipment through the Federal government's Reinforcement Program.

The Management Program to Improve Air Quality in Morelos 2018-2027 (ProAire 2018-2027) (Gobierno del Estado de Morelos, 2019) recognizes the poor conditions of the monitoring network and attributes it to the lack of resources for preventive and corrective maintenance of the stations and their equipment. This document also contains some recommendations derived from technical reviews carried out by third parties, including the federal authority. Some of these recommendations are presented below:

- In 2014, the INECC classified the operation of the network as intermittent during the previous eight years, with insufficient data for the evaluation of air quality standards for the protection of public health..
- The monitoring network must include stations in urban settlements with more than five hundred thousand inhabitants, areas affected by industrial emissions, and in places with

annual emissions into the atmosphere that exceed twenty thousand tons of criteria pollutants of primary origin.

- The state monitoring system lacks facilities, equipment and specialized personnel to guarantee its proper operation.
- There is a lack of spare parts, consumables, and accessories for monitoring equipment.
- There are deficiencies in the cleaning, verification, and validation of data.

Faced with this situation, the local ProAire 2018-2027 contemplates Measure 6.3 “*Strengthening of the Atmospheric Monitoring System of the State of Morelos*” to correct the aforementioned problems. This measure includes twelve actions that, according to the proposed calendar, have not been executed. As of 2021, progress has been limited. A measurement quality control and assurance program should already have been designed and implemented, as well as the network expanded. Between 2018 and 2022, through the Reinforcement Program, various spare parts, meteorological sensors, and equipment for monitoring criteria pollutants, calibration, and data acquisition were provided to the entity.

2.2.4. Puebla

The state of Puebla is located to the southeast of the central plateau, between the Sierra Nevada and the Sierra Madre Oriental. The state surface is part of the physiographic provinces: Sierra Madre del Sur, Neovolcanic Axis, Sierra Madre Oriental and Northern Gulf Coastal Plain. The entity has a diverse geography, to the southwest it is dominated by mountain ranges, while in the center there are plains and hills that separate the mountain ranges in the northwest-southeast direction. The extremes of the central region are framed by large elevations where the Popocatépetl and Iztaccíhuatl volcanoes stand out to the west, and the Pico de Orizaba or Citlaltépetl, to the east. Hills predominate in the north of the entity. About 55% of the territory corresponds to mountains or hills with tectonic or volcanic genesis. It has an important climatic variability; however, the predominant climate is temperate sub-humid.

Approximately 70% of the state territory is suitable for agricultural use. Of this, 55%, located in the center and southeast of the entity, is suitable for technical agriculture, because the soil is flat or with small undulations; the remaining 15% is suitable for agriculture using animal traction and is located throughout the State.

The city of Puebla de Zaragoza is the capital and the most important urban region of the state and is part of the interstate urban corridor known as the Puebla-Tlaxcala Metropolitan Area, which includes 19 municipalities in the state of Puebla and 20 in the state of Tlaxcala. This region concentrates more than three million inhabitants and is located in the center of the entity, it is the fourth most populous metropolitan area in the country. There are two other urban conglomerates with just under 500,000 inhabitants that correspond to the metropolitan areas of Tehuacán to the southeast, and Teziutlán to the northeast. Urban centers concentrate more than 70% of the state's population.

Air quality monitoring is limited to the metropolitan area of Puebla, although efforts have been made to extend air quality monitoring to other regions of the entity. The State Atmospheric Monitoring Network (REMA, *Red Estatal de Monitoreo Atmosférico*) began operations in 2000 with four stations configured for continuous monitoring of criteria pollutants. In 2012, the Velódromo station was incorporated in the municipality of Coronango, northwest of the metropolitan area. The location of the sites is shown on the map in Figure 2.11.

According to the results of atmospheric monitoring, O_3 and particles are the pollutants that most frequently exceed the limit values of the NOMs. As in the other entities, the highest levels of pollution were observed between February and May. According to the 2019 National Air Quality Report (INECC, 2020), air quality standards for O_3, PM_{10} and $PM_{2.5}$ were not met that year. For O_3, 40 days were non-compliance, while for the 24-hour average of PM_{10} and $PM_{2.5}$, non-compliance was recorded on 72 and 14 days, respectively. The annual average for PM_{10} and $PM_{2.5}$ was exceeded in at least one monitoring station.

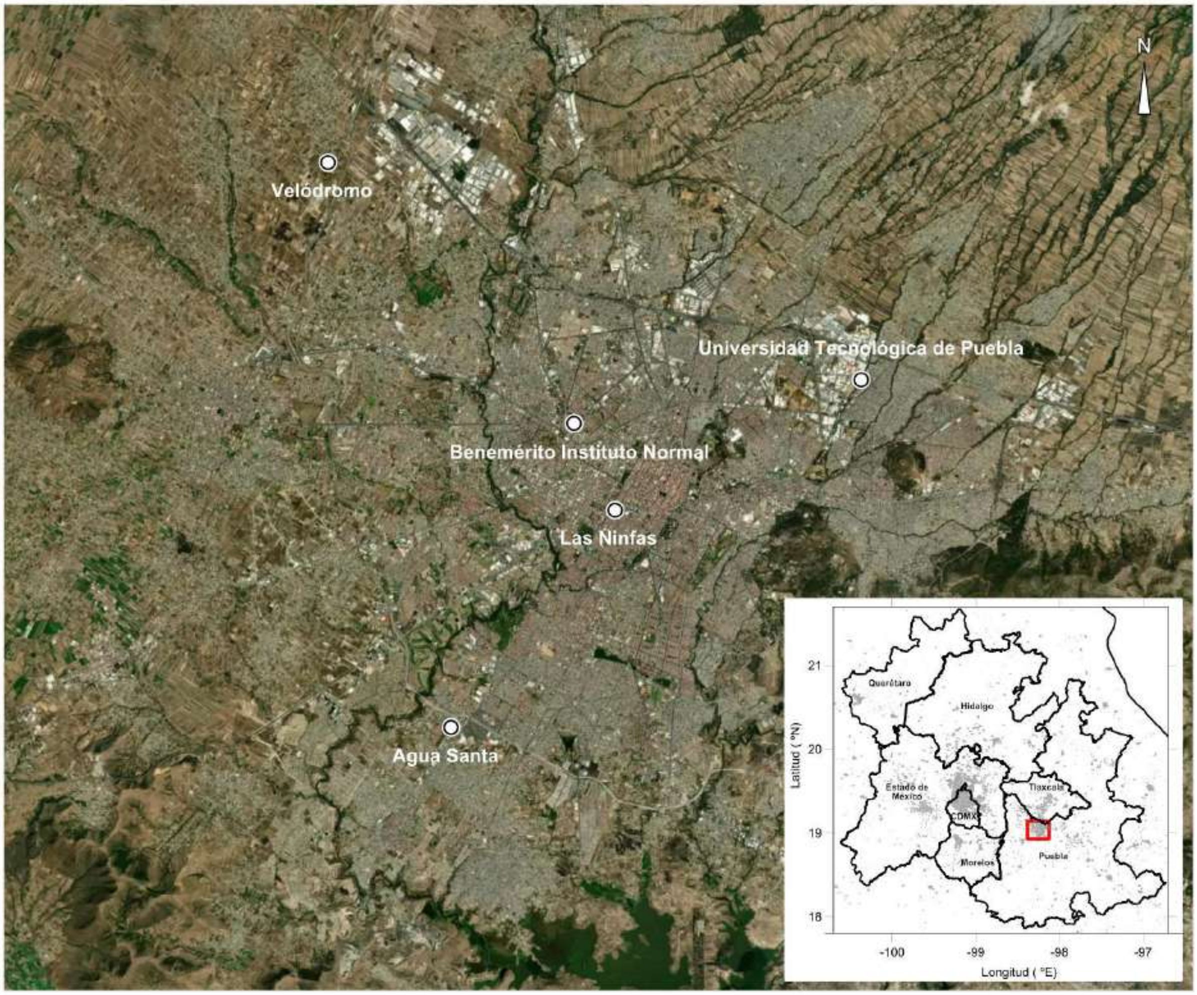


Figure 2.11. Location of continuous monitoring stations in the metropolitan area of Puebla, Puebla. Map updated to July 25, 2022. (Own elaboration with data from SINAICA, accessed on July 25, 2020; image: Google Earth).

Data from the year 2000 do not show a clear trend in any of the pollutants, despite the growth that the metropolitan area of Puebla has experienced in the last two decades. This result is consistent with what was reported in the National Air Quality Report (INECC, 2020). The corresponding figures in Annex B show the time series of the daily averages for the different pollutants during the period 2016 to 2020. In this period, some aspects that suggest operational problems were evident, for example, the time series of CO showed, as in the case of the State of Hidalgo, abrupt changes in the time series. Several of the monitoring stations exhibited inconsistencies in the measured NO_2 concentrations, for example, during the first half of 2018, the Ninfas station reported unusually low concentrations, as did the Agua Santa station in mid-2020. A similar situation was observed for the O_3 data. In the case of SO_2, the situation is even more complicated, since problems with different patterns were observed: periods without changes in the readings (for example, second semester of 2016 at the Benemérito Instituto Normal station), abrupt changes in the measurements (for example, station at the Universidad Tecnológica), or significant changes in trends (for example, 2019 in Agua Santa). Although it is not the purpose of this document to carry out a detailed analysis of the data, it is necessary to consider that the poor quality of the data could hinder its use for management purposes.

The technical evaluation carried out by INECC in 2016 (INECC, 2016) identified aspects of monitoring that required immediate review and issued the following recommendations:

- Relocate the Velódromo, Agua Santa and Benemérito Instituto Normal del Estado stations.
- Review obstructions and obstacles to the free flow of air at the Ninfas, Agua Santa and Benemérito Instituto Normal del Estado stations.
- Timely acquisition of equipment and mixtures of calibration gases.
- Establish a calibration program for particle monitors.
- Replace the instruments used to monitor meteorological variables.
- Have sufficient and trained personnel for the activities included in the monitoring process.
- Establish a documentary record of the maintenance and operation activities carried out on the network.

Some of these observations have been addressed with the delivery of equipment and refurbishment through the Reinforcement Program.

2.2.5. Querétaro

The state of Querétaro is located in the center-east of the country, bordered to the north and northeast by San Luis Potosí, to the east by Hidalgo, to the south by Michoacán, to the north and west by Guanajuato, and to the southeast by the State of Mexico. Its capital, Santiago de Querétaro, is located to the southwest of the entity and together with the municipalities of Corregidora, Huimilpan and El Marqués, they form the Metropolitan Area of Querétaro. With the incorporation into the metropolitan region of the municipality of Apaseo el Alto, Guanajuato, it became an interstate metropolis (SEDATU, 2018). The city of San Juan del Río, to the southeast of the entity, is the second most important city in the state, the corridor that joins both cities is a region with a substantial urbanization process. Commerce and manufacturing are the most important economic activities in the metropolitan area.

The surface of the entity is part of the provinces: Sierra Madre Oriental, Mesa Central and Eje Neovolcánico. The northeast area is made up of mountain ranges and hills, in the central and northern regions, the presence of plateau-shaped mountain ranges continues, and in the central part there are two mountain ranges separated by plains. The climate in the region is warm and semi-warm in the north, dry and semi-dry in the center, and temperate in the south.

Air quality monitoring with automatic equipment began in 2011 and has been concentrated in the urban region. Until 2019, there were six monitoring stations in the Querétaro Metropolitan Area and one in San Juan del Río. In 2020 the Cultural Center station was added. In 2021, the Epigmenio González and Josefa Vergara stations were incorporated, and the Carrillo Puerto and El Marqués sites were relocated. Figure 2.12 shows the location of the monitoring stations updated to July 2022.

According to the 2019 National Air Quality Report (INECC, 2020), the concentrations of O_3, PM_{10} and $PM_{2.5}$ exceeded the limit values of the air quality standards that year. The pollutant that had the greatest contribution to the deterioration of air quality was PM_{10}, while in El Marqués and San Juan del Río it was O_3. In Santiago de Querétaro there were 108 days with poor air quality, in El Marqués 12 days and in San Juan del Río 16 days.

The highest O_3 concentrations were observed between March and May, while those of particles occurred throughout the dry season (November to May). The absence of data for prolonged periods was observed at several of the monitoring stations. In addition, deficiencies in the quality of the data were identified, mainly in the measurements of CO, SO_2 and NO_2.

The operation of several stations has been discontinued since its inception due to problems related to failures in some services and limitations in resources and infrastructure (SEDESU, 2014). The lack of data makes it difficult to identify seasonal patterns and trends. Recognizing the above, in 2020 the local authorities began efforts to improve the work carried out in the monitoring network. Among the aspects reviewed were the replacement of obsolete equipment, the relocation of some unrepresentative stations, the increase in operational personnel, the acquisition of spare parts and consumables for the operation, the implementation of a workshop for maintenance and calibration of equipment, and the development of a quality assurance and control program. The results of this effort are expected to be reflected in the quality of the data starting in 2021.

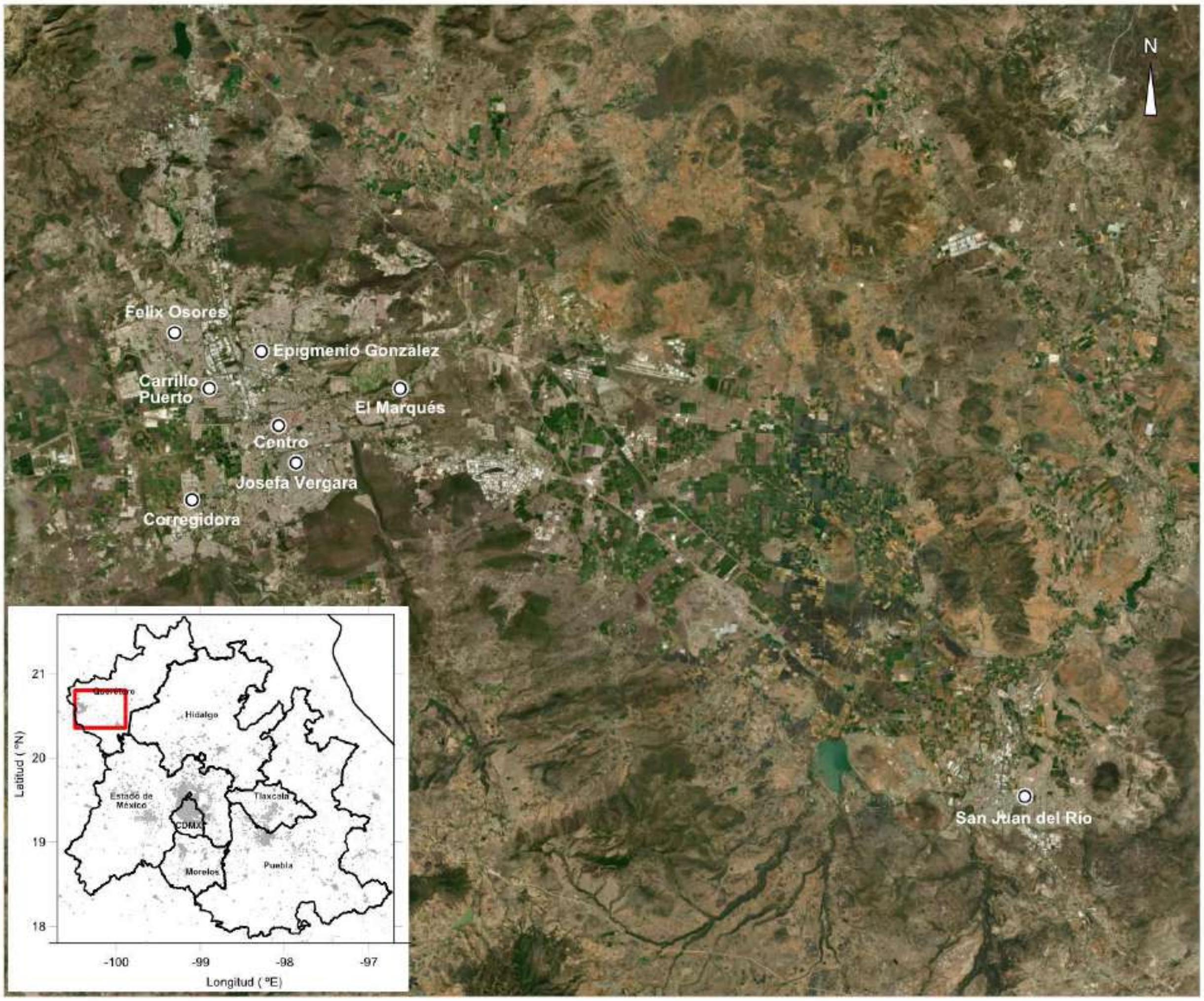


Figure 2.12. Location of the continuous monitoring stations in the metropolitan area of Santiago de Querétaro and in the municipality of San Juan de Río, Querétaro. Map updated to July 2022. (Own elaboration with data from SINAICA, accessed on July 25, 2022; image: Google Earth).

2.2.6. Tlaxcala

The state of Tlaxcala is located in the center west of the country, in the physiographic province Eje Neovolcánico. It borders the State of Mexico to the west, Hidalgo to the northwest, and Puebla to the north, east and south. Its relief is characterized by extensive plains to the northwest and southeast, in the west there are mountain ranges where the La Malinche volcano (4420 masl) stands out. To the east, hills and mountain ranges predominate. The climate is temperate sub-humid with rain during the summer.

The population is concentrated in three main regions: south (Zacatelco), south-central (Tlaxcala) and north-central (Apizaco). The entity has two metropolitan areas that concentrate more than 70% of the population, Puebla-Tlaxcala and Tlaxcala-Apizaco, the first with an interstate conurbation and the second with an intermunicipal conurbation.

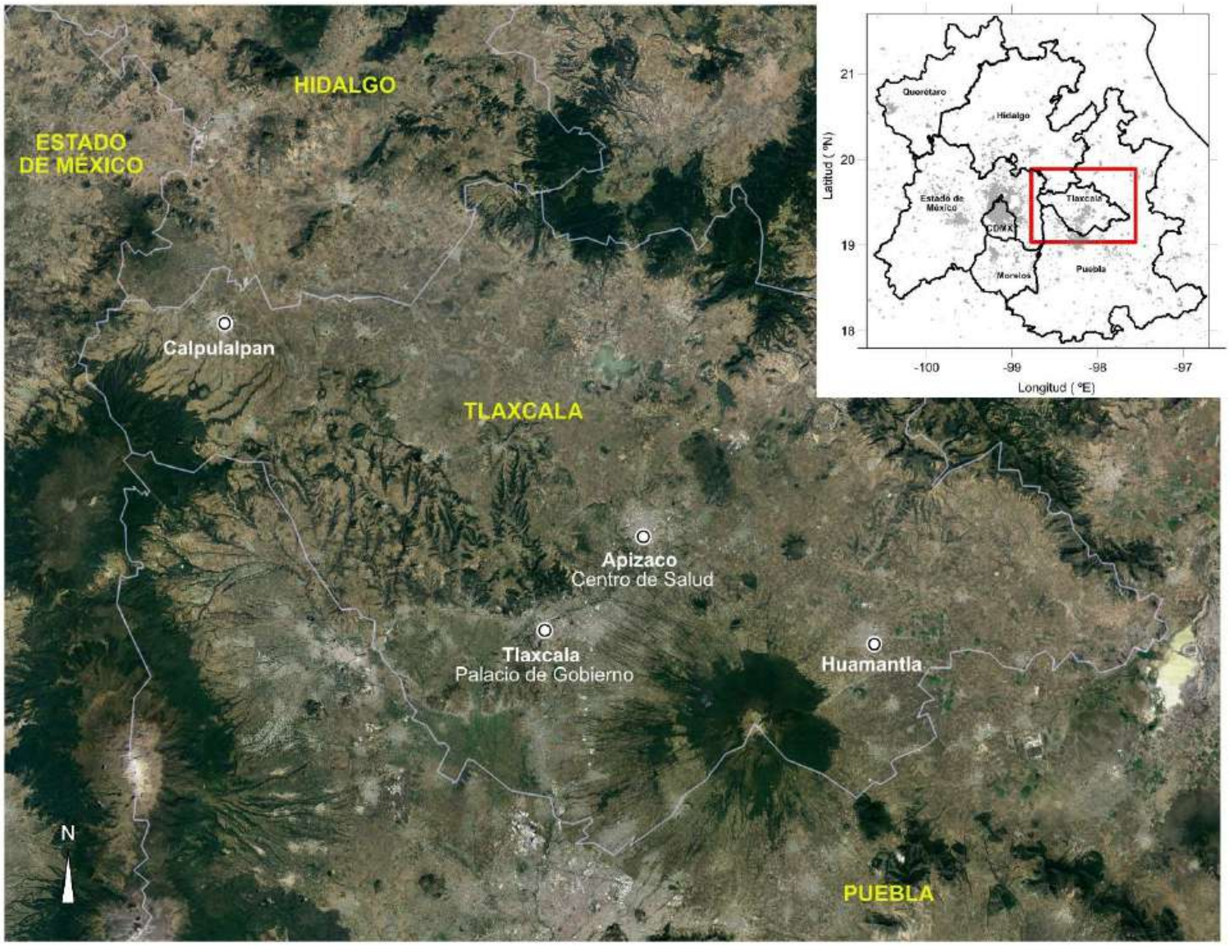


Figure 2.13. Location of the continuous monitoring stations in the state of Tlaxcala. The text indicates the names of the municipality and the station. Map updated to July 2022. (Own elaboration with data from SINAICA, accessed on July 25, 2022; image: Google Earth.).

The entity had a monitoring network with manual stations for measuring PM_{10} and total suspended particles (TSP), which was in operation between 2011 and 2016. As of 2017, this network was replaced by one made up of four stations with continuous automatic equipment (see Figure 2.13). Currently, monitoring of the criterion pollutants PM_{10}, $PM_{2.5}$, O_3, SO_2, NO_2 and CO is carried out at the Tlaxcala and Apizaco stations, while only $PM_{2.5}$ is measured in the two remaining stations, Huamantla and Calpulalpan. Measurements have been carried out in the monitoring network since 2017, except for the Apizaco station, where monitoring began in 2019. The validated data available in SINAICA for the Tlaxcala station show a behavior that does not correspond to atmospheric dynamics and that suggests possible deficiencies in the operation of the equipment as can be seen in Figure 2.14. The 2019 National Air Quality Report did not include a description of the air quality for this entity.

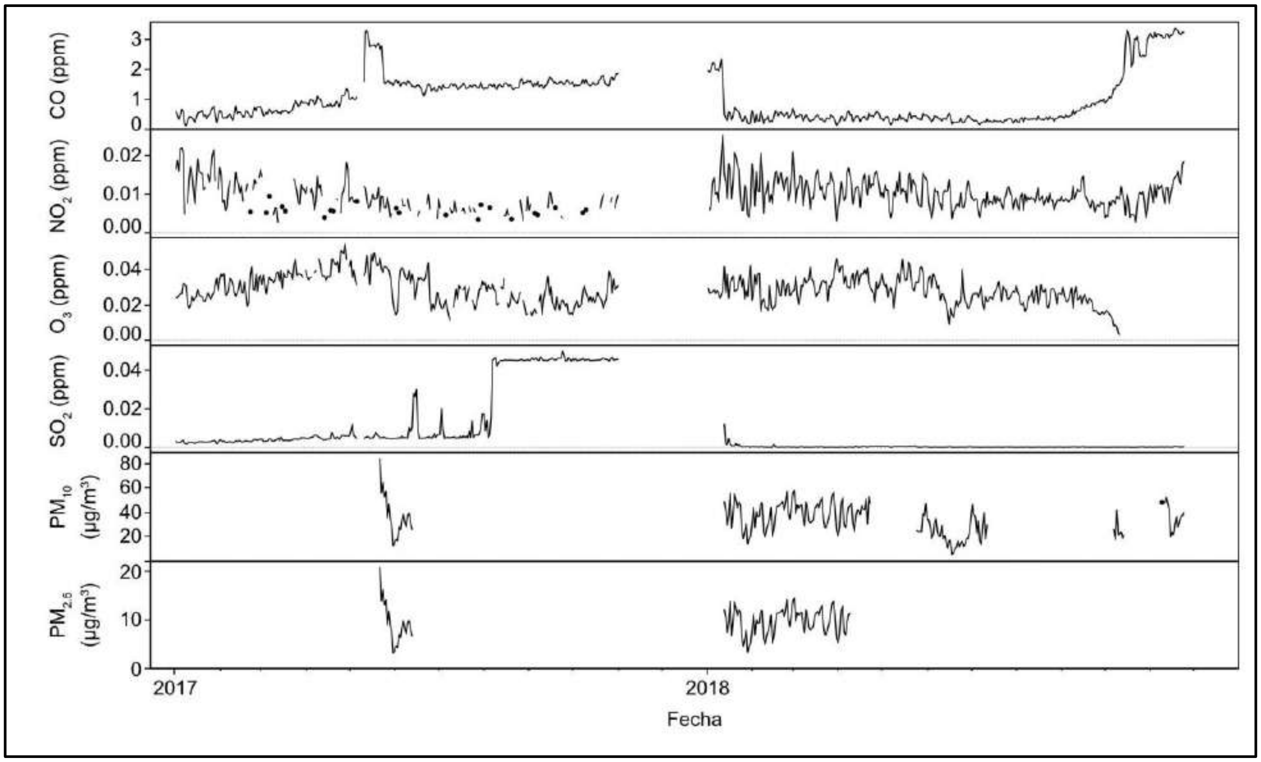


Figure 2.14. Time series of the hourly averages of the air quality data for the city of Tlaxcala. (Own elaboration with data from SINAICA, accessed on July 25, 2022).

2.3. Comparison of the air quality between the cities of the Megalopolis

Despite the uncertainty that the monitoring data might have, it is necessary to recognize that they are the only ones available to assess the air quality situation in the region. As can be derived from this review, in some cases the data generated by the networks should be considered as indicative of air quality. Taking the above into account and with the purpose of obtaining some information about the regional air quality situation, a comparison was made of the annual averages obtained in the different monitoring systems that operate in the Megalopolis region. The results are presented in Figures 2.15 to 2.20, which show the distribution of the annual averages reported by each of the monitoring stations of the different systems for the period 2016-2020. In the case of the SIMAT stations, these were classified according to the entity in which they were located; those that were in the suburban municipalities of the State of Mexico were included in the so-called Cuautitlán-Texcoco metropolitan area (consistent with the ProAire of the State of Mexico), the rest of the stations corresponded to Mexico City. In the calculation of the annual average, only the years with more than 75% of valid hourly data were used. For each chart, the diagrams were arranged according to the magnitude of the global average (when more than two data points were available) ordering the cities from the highest to the lowest level of pollution. It is important to mention that the absence of data in several monitoring systems was evident, adding greater uncertainty to the analysis.

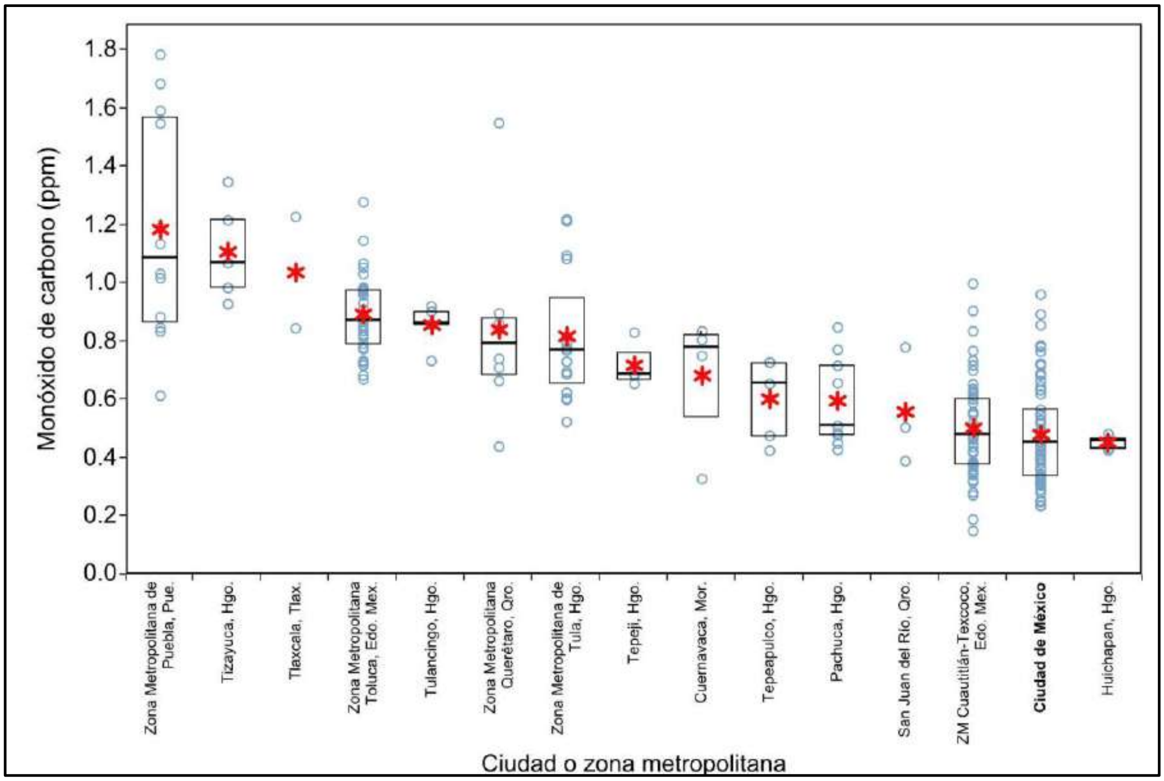


Figure 2.15. Distribution of the annual averages of carbon monoxide (CO) in each of the urban areas that have continuous monitoring in the region of the Megalopolis for the period 2016-2020. The blue circles correspond to the annual average value of each of the monitoring stations. The stars in red indicate the mean of the averages observed at the monitoring stations in each locality. For those cities that have five or more values, a box is shown with the values of the 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

In the case of CO (Figure 2.15), the Cuautitlán-Texcoco Metropolitan Area, Mexico City, and Huichapan, Hidalgo, reported the lowest average concentrations, while the metropolitan area of Puebla presented the highest values. This result is striking, since CO is a pollutant directly linked to automobile exhaust emissions and the MCMA has the highest number and density of vehicles in the region. An interpretation of these results could be related to the strict control of emissions maintained by the MCMA through the Vehicle Verification Program, as well as the age of the fleet - which is the youngest in the region. However, as mentioned above, during the review of the data, it was observed that most of the monitoring systems have problems correctly measuring this pollutant. The uncertainties in the measurements are not consistent for all the monitoring equipment, they can be different even for the equipment used within the same monitoring system; consequently, it is difficult to establish a common correction factor for each monitoring system. For an objective evaluation, it will be necessary to carry out the review station by station. Although CO does not exceed the limit levels of the standard, it is relevant since it is usually used as a tracer gas for vehicle emissions, and is useful for evaluating the progress in vehicle verification programs, in addition to being used as a proxy for other pollutants associated with vehicular traffic (for example, hydrocarbons).

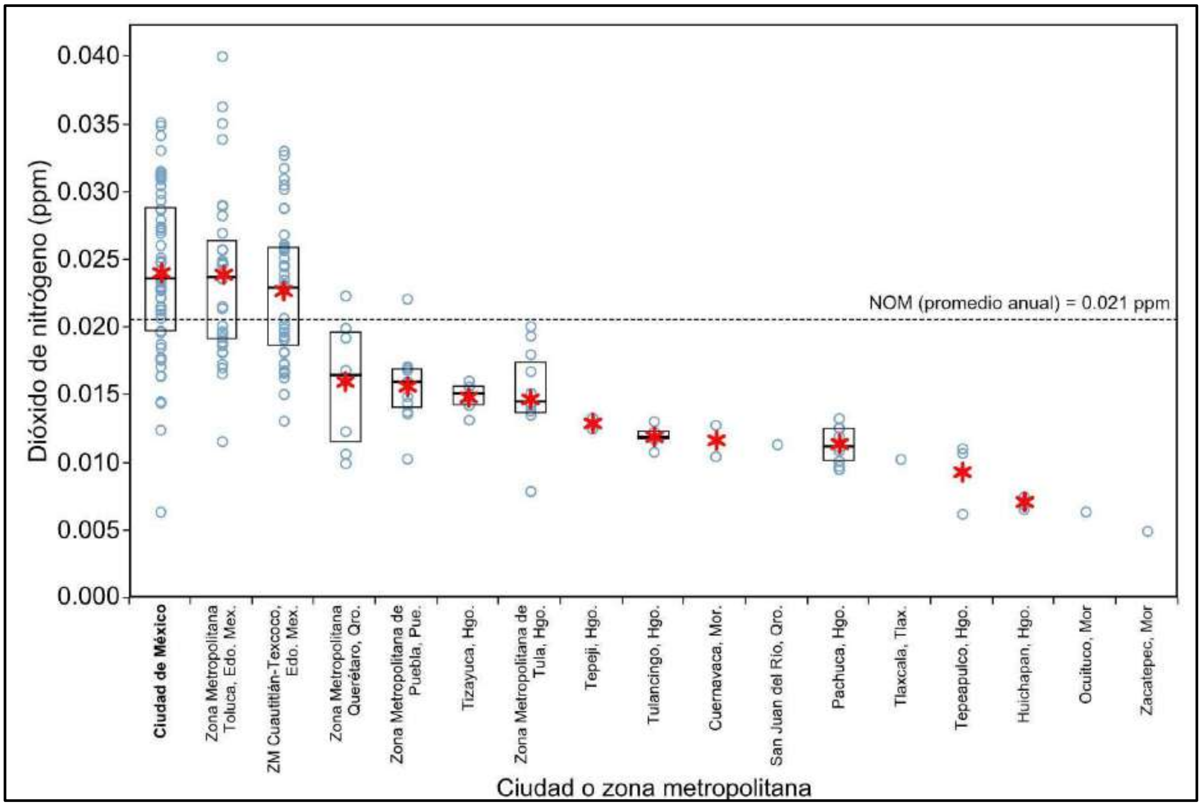


Figure 2.16. Distribution of the annual averages of nitrogen dioxide (NO_2) in each of the urban areas that have continuous monitoring in the region of the Megalopolis, for the period 2016-2020. The blue circles correspond to the value of the annual average of each of the monitoring stations. The stars in red correspond to the mean of the averages observed at the monitoring stations of each locality, for those cities that have five or more values, a box is shown with the values of the 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. The dotted line indicates the limit value of NOM-023-SSA1-2021 for the annual average. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

Nitrogen dioxide (NO_2) plays an important role in atmospheric chemistry and has important effects on health, so its concentration in ambient air is regulated. Mexico City and the Toluca metropolitan area registered the highest averages, both with values of 24 ppb. The Cuautitlán-Texcoco metropolitan area followed with an average of 23 ppb (see Figure 2.16). The city of Tizayuca and the metropolitan areas of Querétaro, Puebla and Tula presented similar averages, with values between 15 and 16 ppb. In the rest of the cities, the averages were in the range of 5 to 13 ppb; however, the data was scarce for most of the small cities. The fact that there is no significant difference between the average concentrations of the metropolitan areas of Mexico City, Cuautitlán-Texcoco and Toluca stands out.

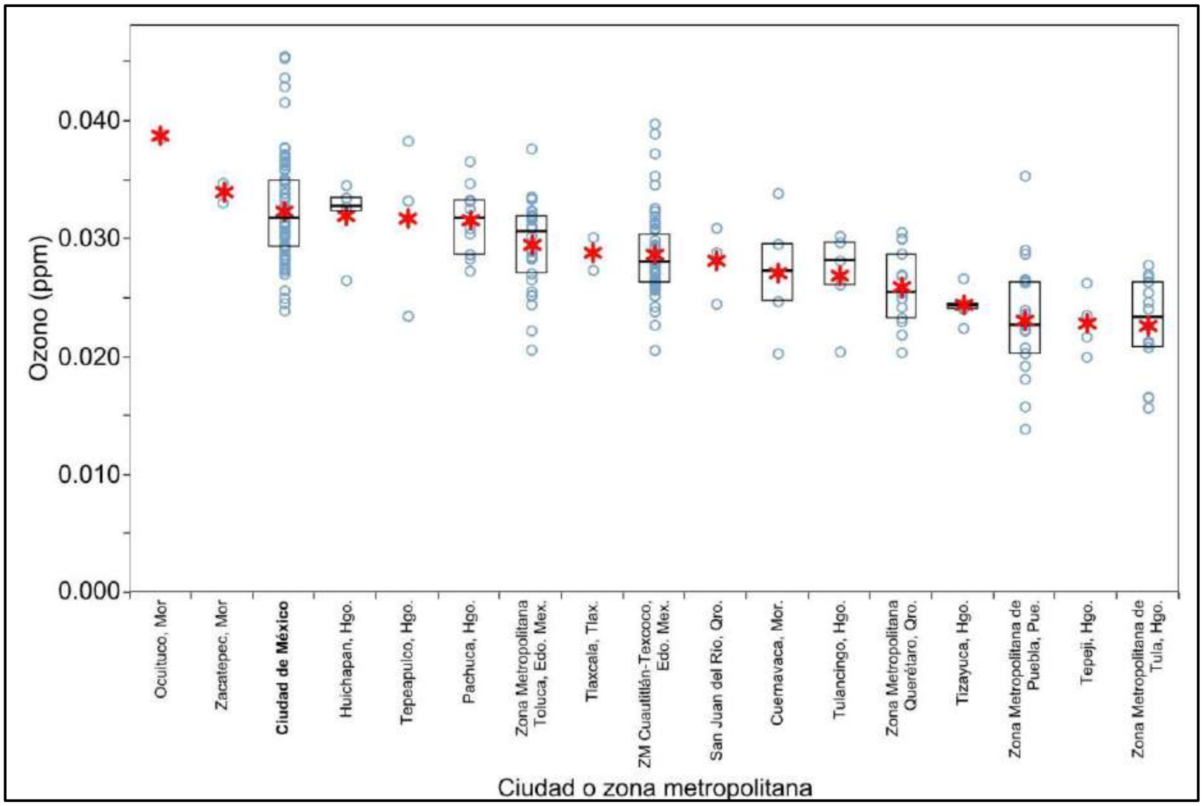


Figure 2.17. Distribution of the annual ozone averages in each of the urban areas that have continuous monitoring in the Megalopolis region, for the period 2016-2020. The blue circles correspond to the value of the annual average of each of the monitoring stations. The stars in red correspond to the mean of the averages observed at the monitoring stations of each locality, for those cities that have five or more values, a box is shown with the values of the 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

Mexico City is characterized by high O_3 levels, mainly between mid-February to mid-June. This period, for environmental management purposes, has been known as the O_3 season. Therefore, it was not surprising that it had the highest global averages (32 ppb). However, several cities in Hidalgo (Huichapan, Tepeapulco and Pachuca) presented the same average, 32 ppb. The urban conglomerates of the State of Mexico also registered very similar averages, 30 ppb in the Toluca metropolitan area and 29 ppb in the metropolitan area of Cuautitlán-Texcoco (see Figure 2.18). The urban areas of Ocuituco and Zacatepec, Morelos, reported higher averages than those of Mexico City in 2018 and 2019. The lowest average was observed in the Tula metropolitan area with a value of 23 ppb. The results suggest that O_3 pollution was present throughout the region.

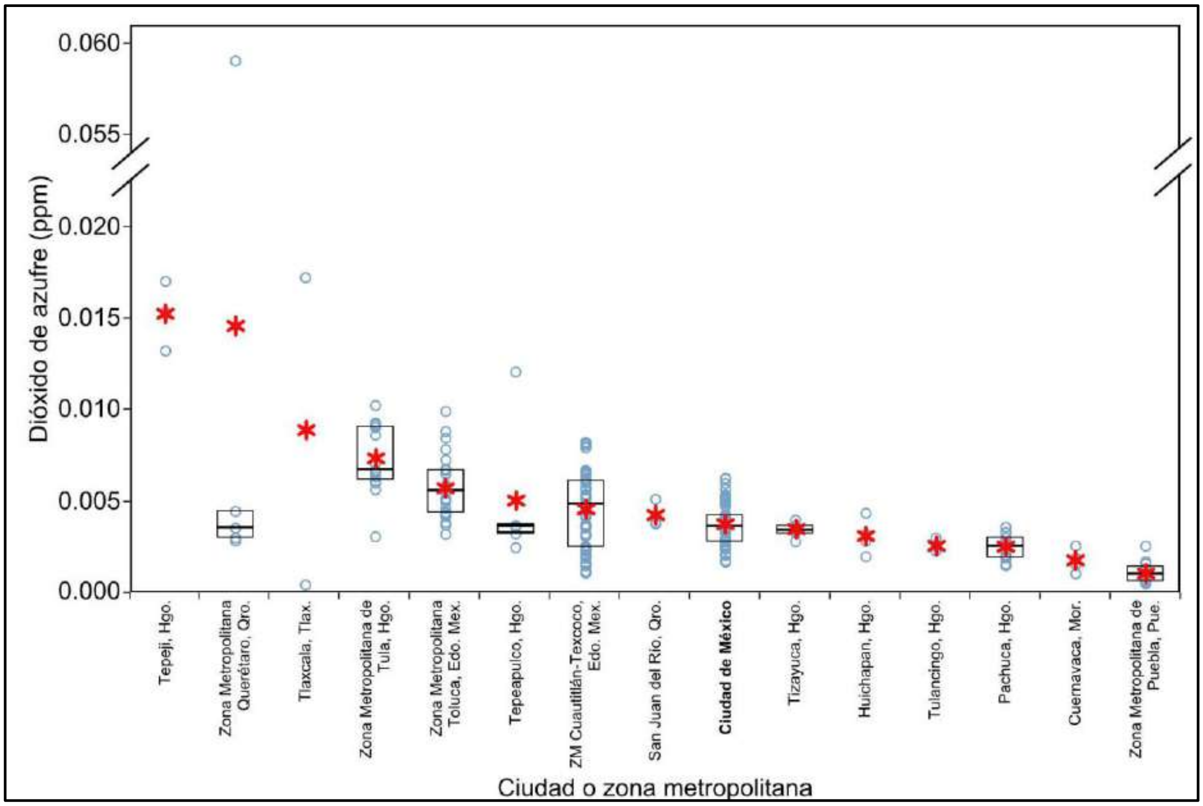


Figure 2.18. Distribution of the annual averages of sulfur dioxide in each of the urban areas that have continuous monitoring in the region of the Megalopolis, for the period 2016-2020. The blue circles correspond to the value of the annual average of each of the monitoring stations. The stars in red correspond to the mean of the averages observed at the monitoring stations of each locality. For those cities that have five or more values, a box is shown with the values of the 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

Sulfur dioxide (SO_2) pollution is closely associated with fuel consumption, mainly diesel and fuel oil. This explains why the urban areas with the highest industrial activity reported the highest SO_2 levels, including Tepeji, Tlaxcala, and the metropolitan area of Querétaro. The metropolitan areas of Tula, Toluca and Cuautitlán-Texcoco presented average values between 5 and 7 ppb, exceeding the average concentration observed in Mexico City (4 ppb) (see Figure 2.18). During the review of the data, it was observed that several monitoring networks could have problems to correctly determining low SO_2 concentrations; abrupt changes in trends frequently occurred, as well as very high or low readings.

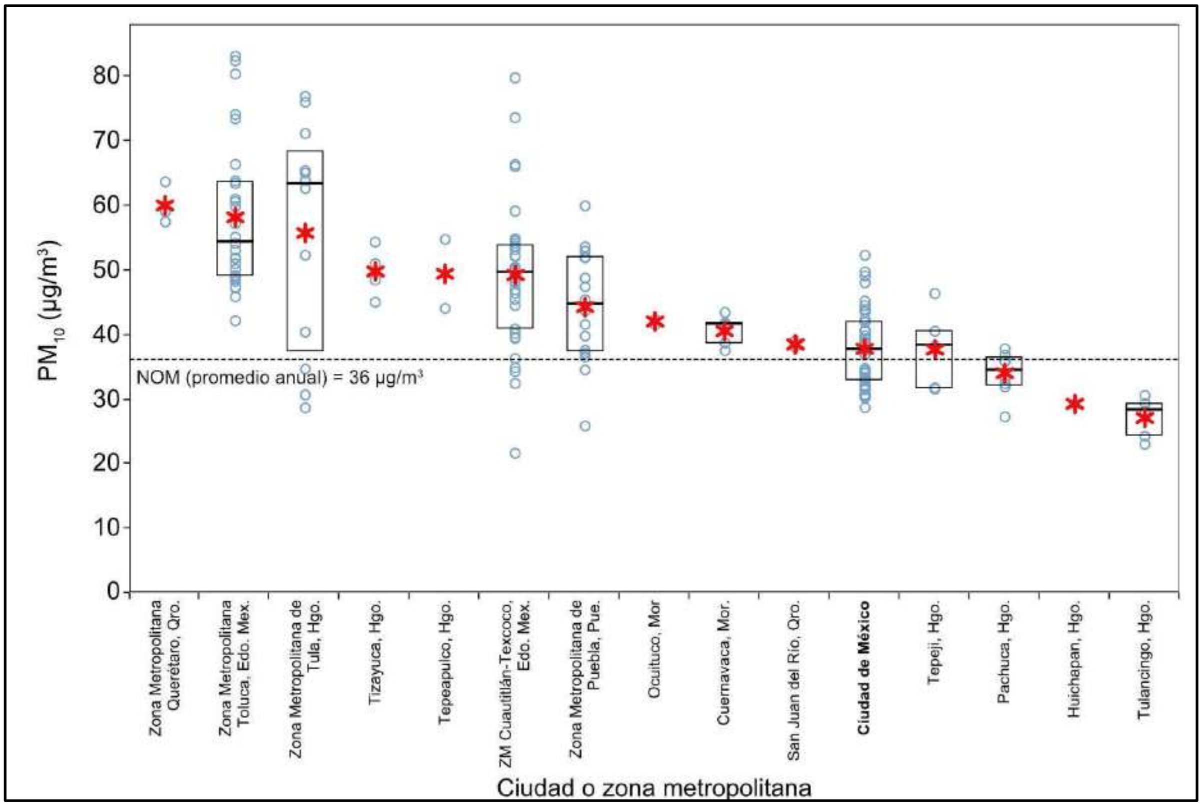


Figure 2.19. Distribution of the annual averages of PM$_{10}$ in each of the urban areas that have continuous monitoring in the region of the Megalopolis, for the period 2016-2020. The blue circles correspond to the value of the annual average of each of the monitoring stations. The stars in red correspond to the mean of the averages observed in the monitoring stations of each locality. For those cities that have five or more values, a box is shown with the values of the 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. The dotted line indicates the limit value of NOM-025-SSA1-2021 for the annual average. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

The data suggests that PM$_{10}$ pollution is a problem in most of the urban settlements in the region (see Figure 2.19). The highest averages were observed in the metropolitan areas of Querétaro, Toluca, and Tula, with values of 60, 58 and 56 µg/m^3, respectively. In comparison, Mexico City recorded an average of 38 µg/m3. With the exception of Huichapan and Tulancingo, Hidalgo, the limit value of the standard (NOM-025-SSA1-2021) of 36 µg/m^3 for the annual average was exceeded in the rest of the urban conglomerates.

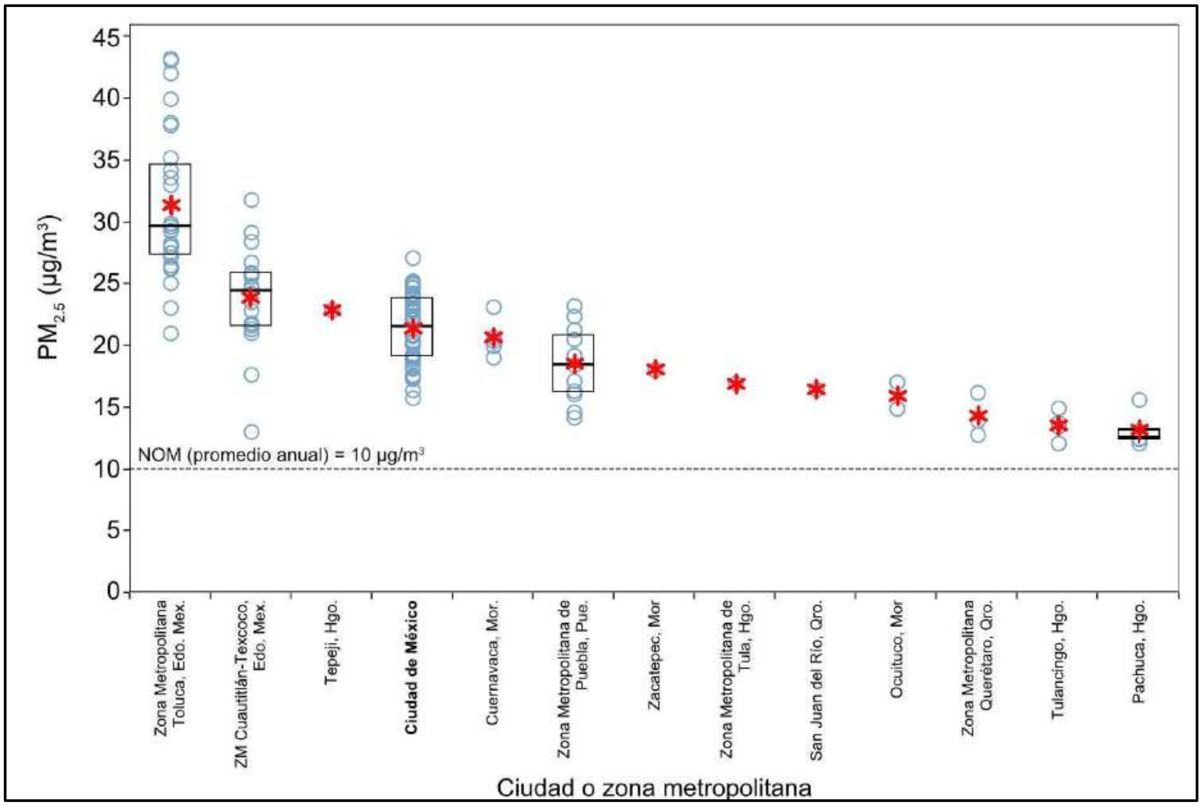


Figure 2.20. Distribution of the annual averages of $PM_{2.5}$ in each of the urban areas that have continuous monitoring in the region of the Megalopolis, for the period 2016-2020. The blue circles correspond to the value of the annual average of each of the monitoring stations. The stars in red correspond to the mean of the averages observed in the monitoring stations of each locality. For those cities that have five or more values, a box is shown with the values of 75th (upper line), 50th (middle line) and 25th (lower line) percentiles. The dotted line indicates the limit value of NOM-025-SSA1-2021 for the annual average. (Own elaboration with data from the Air Quality Monitoring Directorate and SINAICA, accessed on July 25, 2022).

The information available for $PM_{2.5}$ is scarce or none in most urban areas of the Megalopolis, despite the fact that it is the pollutant that has the greatest impact on public health. The main urban conglomerates of the State of Mexico registered the highest values, with averages of 31.3 and 23.9 µg/m^3 in the metropolitan areas of Toluca and Cuautitlán-Texcoco, respectively. Mexico City recorded an average of 21.3 µg/m^3. Pachuca, Hidalgo, reported the lowest average with a value of 13.2 µg/m^3. As can be seen in Figure 2.20, the annual averages reported in all monitoring networks exceeded the limit value of 10 µg/m^3 for the annual average established by NOM-025-SSA1-2021.

2.4. The Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis

The episodes of O_3 pollution in 2016 in Mexico City marked a watershed in the management of air quality in the region. Although the causes of the phenomenon are still under study, the political impact motivated the federal authorities to carry out an in-depth review of the state of air quality management in the Megalopolis. As a result, CAMe proposed a set of actions, including an important investment to strengthen monitoring capacities in the region and the creation of an approved platform for the dissemination of air quality information (SEMARNAT, 2016). This commitment led to the establishment of the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis (*Programa de Reforzamiento de las Capacidades de Monitoreo de la Calidad del Aire en la Megalópolis*) with an investment of 150 million pesos from the National Infrastructure Fund (FONADIN, *Fondo Nacional de Infraestructura*), aimed at strengthening the monitoring infrastructure and supporting a Megalopolitan Air Quality Monitoring System (CAMe, 2020). Its implementation began in 2017 with an execution period of 5 years and the following objectives:

- Observe compliance with the Official Mexican Standards related to public health and the measurement of air pollutants.
- Ensure the generation of reliable information on air quality in the Megalopolis region.
- Strengthen the existing air quality monitoring infrastructure by replacing obsolete equipment with major failures as well as with the acquisition of spare parts for the other equipment.
- Expand the existing atmospheric monitoring networks to cover cities with more than 500,000 inhabitants in the CAMe region and relevant areas due to the transport of pollutants between atmospheric basins.
- Expand the range of air pollutants monitored through the acquisition of equipment for the detection of ultrafine particles and black carbon.
- Implement the Megalopolis Air Quality Network (CAMe AIR, *Red de Calidad del Aire Megalópolis*) as a subsystem of the Megalopolis Air Quality Monitoring System.
- Provide environmental authorities with information for the design and implementation of policies, programs, and actions to reduce pollution and protect public health.
- Disseminate validated information on the concentration of pollutants in the region among the population in order to prevent their exposure and adverse health effects.

The detail of the assets and the amount of the investment in each entity is described below:

- Mexico City: 45 equipment and 4 vehicles ($26,413,235).
- State of Mexico: 3 monitoring stations, 23 equipment, 2 vehicles and spare parts ($27,980,313).
- Hidalgo: 17 teams, 1 vehicle and spare parts ($15,625,522).
- Morelos: 29 pieces of equipment and spare parts ($15,189,355).
- Puebla: 22 pieces of equipment and spare parts ($16,419,293).
- Tlaxcala: 1 monitoring station ($4,879,313).
- INECC: 2 analyzers, 2 mobile units for the speciation of aerosols and atmospheric profiles ($39,430,000).

The instruments not only included air quality monitoring equipment, but it also included data loggers, calibration equipment, and meteorological sensors. As of December 2022, the Program reported a physical and financial progress of 94% (Gobierno de México, 2023).

The environmental authorities are confident that this project will contribute to solving the main infrastructure problems of the region's monitoring systems and that this will be reflected in better data quality. Analysis of the impact of this program on addressing previous audit observations and improving data quality is outside the scope of this document.

2.5. Satellite observations

Air quality monitoring provides information on the concentrations of air pollutants at different temporal and spatial scales. This is achieved through atmospheric monitoring networks that integrate a number of stations distributed in the region of interest. These networks tend to be concentrated mainly in urban areas, so they provide limited information on the spatial distribution of pollutants outside them. Likewise, in practice it is difficult to change the location of the monitoring stations and modify the configuration of the monitoring networks along with the growth of cities and changes in their topology and morphology. To mitigate these limitations, air quality monitoring networks are often complemented with numerical models and satellite data. In the case of the Megalopolis, the monitoring networks have limited coverage and most of the region is underrepresented, as already described.

The data on the chemical composition of the atmosphere generated by various satellite missions are a resource that has begun to be used to complement the monitoring of air quality through networks of surface stations (Anenberg et al., 2020). Furthermore, the launch of new geosynchronous orbit satellites makes it possible to obtain data with unprecedented spatial and temporal resolutions (Judd et al., 2018, CEOS, 2019). The TEMPO (Tropospheric Emissions: Monitoring of Pollution) of the National Aeronautics and Space Administration (NASA), launched in April 2023, will permanently cover North America, including much of the Republic of Mexico. The instruments mounted on TEMPO will provide measurements of O_3, NO_2, CO, methane (CH_4), and other species important in daily atmospheric chemical cycles. The data will allow the evaluation of pollution during peak hours in urban and suburban areas, the transport of pollution from biomass burning and O_3 production, as well as the identification of pollution from specific sources.

2.5.1. Capacities in Mexico for the use and exploitation of satellite data

In Mexico, the Spectroscopy and Remote Sensing group at ICAyCC-UNAM is the main research team dedicated to the analysis and validation of satellite data. This group is currently collaborating with NASA for the use and exploitation of the data that TEMPO will produce for the case from Mexico.

It is necessary that the environmental authorities of the entities of the Megalopolis become involved in the use of these new sources of information on air quality to strengthen their atmospheric monitoring capacities of air quality. The National Institute of Public Health (INSP, *Instituto Nacional de Salud Pública*) has already taken the initiative in the use of satellite products.

They have been used in combination with data from surface monitoring stations to reconstruct $PM_{2.5}$ exposure spatially and temporally for epidemiological studies (Just et al., 2015; Téllez-Rojo et al. al., 2018; Tamayo-Ortiz et al., 2021).

2.6. Hybrid monitoring systems

From the point of view of environmental management, progress must be made towards the construction of monitoring networks in a hybrid scheme, in which atmospheric monitoring stations equipped with regulatory-grade equipment and research-grade instruments mounted on fixed platforms and mobile phones with low-cost monitors and satellite data (see Annex A of this chapter). In this way, monitoring networks will be able to provide more and better information on air pollution with greater spatial and temporal resolutions (Gani et al., 2022). The application of hybrid schemes will require adequate planning, the availability of human and financial resources, and a long-term vision. The following aspects should be considered to advance the deployment of hybrid monitoring systems:

- It is urgent to improve regulatory monitoring and harmonize existing networks in the region.
- It is essential to establish and enforce quality assurance and control protocols and activities for regulatory atmospheric monitoring.
- It is necessary to expand the scope of current air quality monitoring network. Low-cost sensors and satellite products alone will not be able to cover the missing regions. The accuracy of the data depends on the readings being properly calibrated against *in-situ* measurements with regulatory-grade monitors.
- It is essential to design methods for monitoring, data collection and validation, and dissemination of results in a harmonized manner. It is necessary to develop algorithms that adjust and harmonize the data from low-cost sensors and satellite products. The information generated must be available to all users in simple and accessible formats.
- The information technology infrastructure must be in place to manage the data generated by the regulatory-grade atmospheric monitoring stations, scientific instruments, low-cost monitor networks, and satellite products.
- It is essential to have the technical and research capabilities to develop and sustain the operation of hybrid atmospheric monitoring system. For example, TEMPO products cannot be used until the necessary infrastructure and human resources are available for their application and daily use.
- Policies and regulations will be required for the use and exploitation of devices other than regulatory-grade instruments (for example, low-cost sensors).
- The entities that make up the Megalopolis should coordinate efforts for the development of technical capacities, data management, the development of policies and regulations for the use and exploitation of data from the different measurement methods, and to build platforms in which the information generated can be shared and disseminated. This will require funding mechanisms to be established to ensure the sustainability of this monitoring scheme.

2.7. Challenges and recommendations for air quality monitoring in the Megalopolis

2.7.1. *Challenges of air quality monitoring in Mexico City*

The main problem facing the Mexico City atmospheric monitoring network is its sustainability due to lack of budget for its operation and maintenance. Despite the importance of SIMAT for environmental management, improving air quality and protecting public health in the MCMA, it has a limited budget. In 2022, the allocated budget in the Annual Operating Program (POA, *Programa Operativo Anual*) for the “Atmospheric monitoring and emissions of other pollutants” (*Monitoreo atmosférico y emisiones de otros contaminantes*) program was $14,369,145, of which only $3,429,583 were allocated for the purchase of spare parts, consumables, and accessories (Secretaría de Administración y Finanzas, 2022), comparatively the network would require around $10 million pesos per year in this area. Less than 40% of the remaining budget was allocated to the payment of basic network services for the operation of the network (for example, maintenance of air conditioning in monitoring stations, miscellaneous expenses such as fuel and maintenance of vehicles necessary for maintenance and supervision tasks). The rest of the budget is allocated to other activities related to air quality management.

The budget is insufficient to meet the basic needs of the operation and maintenance of the atmospheric monitoring network. It represents less than 30% of the necessary resources. The deficit is usually covered with extraordinary resources from different funds; however, these resources are not fixed and can change from year to year depending on the priorities of each administration. Restriction on budget allocations make it difficult to timely renew damaged or obsolete instrumentation. In the last two decades, the acquisition of new equipment has been carried out mainly with federal resources (RAMO 16 or FONADIN) or from different local funds (for example, the Environmental Fund).

The lack of an adequate budget makes it difficult to plan the operation of the network in the medium and long terms, in addition to compromising its technological validity. It has even been necessary to temporarily suspend the operation of up to 30% or more of the monitoring stations to reduce operating costs in years with severe resource constraints.

The SIMAT generates information on air quality for Mexico City and the Cuatitlán-Texoco conurbation area of the State of Mexico, so it is recommended to explore financing mechanisms that involve both environmental authorities of Mexico City and the State of Mexico, as well as the federal government. The recent contribution of equipment and vehicles through the Reinforcement Program is an example of this type of participation for the benefit of both entities.

Regarding the distribution of network stations, it would be advisable to identify the presence of redundancy in the measurements. It is possible that it is not necessary to measure certain pollutants in some places due to their low variability with respect to others. If so, operating costs could be reduced without affecting spatial and temporal coverage, and such resources could be used to expand network coverage.

It is also necessary to continue with the evaluation and introduction of new technologies for the measurement of CO, SO_2 and NO_2, as has been done recently with the resources provided by the Reinforcement Program. This will reduce the uncertainty in the measurements and generate data with greater precision. SIMAT must continue with the characterization of the species involved in the formation of secondary pollutants, the monitoring of reactive species, resume the intensive measurement campaigns that were carried out during critical pollution seasons, and encourage and participate in the design and execution of research campaigns in collaboration with national and international institutions.

2.72. Challenges of air quality monitoring in the Megalopolis

Although air quality monitoring in most of the entities that make up the Megalopolis has been carried out for more than a decade, with the exception of SIMAT in Mexico City, there are some uncertainties about the data generated by some entities. As described in this chapter, all monitoring networks present problems in operation, maintenance, and control and assurance in the quality of their records.

In this context, the work carried out by SIMAT is notable, which, despite not having the necessary financial resources, but thanks to the commitment and work of its engineers and technicians, has maintained a constant quality throughout the last two decades. This makes it possible to know the trend and evolution of air pollution in the city, and thus to objectively assess the impact of changes in environmental regulations, the introduction of new technologies and emission controls, the growth of the urban area, the change in land use in some sectors of the city, and the impact of climate change.

In terms of age, the atmospheric monitoring systems of Toluca and Puebla follow that of Mexico City; however, they have not been able to replicate the effectiveness of SIMAT in generating reliable and robust information. The monitoring systems of Hidalgo and Querétaro are relatively incipient and are still in the development phase, but with notable advances. The monitoring systems of Morelos and Tlaxcala require effort and commitment from local authorities to begin producing data with sufficient quality for use in decision-making and addressing management needs.

From the review of the air quality monitoring systems in the Megalopolis region, the following observations emerge:

- According to the available data, Mexico City is not the most polluted city in the Megalopolis. The pollution levels observed in several cities in the region are similar or higher than those observed in Mexico City.
- The origin and transformation of air pollutants in the different cities and regions of the Megalopolis are not necessarily the same as in Mexico City. Therefore, it is necessary for each entity to generate local data that contributes to understanding the causes and risks of the pollution that affects them. The design of the monitoring networks must reflect their own needs according to the local problems.
- The Megalopolis region is underrepresented by atmospheric monitoring. There are significant gaps in knowledge about the spatial distribution of air pollutants at both the urban and regional scales. There is little evidence on the situation of air quality in rural

areas, areas of ecological value, agricultural areas (important for food security) and small towns.

- There are challenges in reducing the disparity in data quality between different monitoring systems. In some cases, the data have uncertainties that are difficult to quantify, limiting their use for air quality management and public information.
- Some air quality monitoring systems do not perform adequate validation before publishing their data in their local repositories or in SINAICA. Deficient data should be identified and invalidated during the monitoring process, prior to publication. On the other hand, the approval and publication of these data in the SINAICA repository gives a false sense of confidence to those monitoring networks that are producing poor data.
- The lack of financial, technical, or human resources is a constant in all monitoring systems. This is an important limitation that must be addressed since the air quality management and the public health protection rely on them.
- Most monitoring systems do not have an adequate data quality management program.
- All monitoring systems report concentrations that exceed the limit values of the Official Mexican Standards, mainly for O_3, PM_{10} and $PM_{2.5}$. The highest concentrations of O_3 are observed from March to May, while those of suspended particles are observed between November and May, during the dry season. Between June and October, during the rainy season, pollution levels decrease throughout the region. It is important to take into account that two of the most polluted days in all states usually occur during Christmas and New Year’s day due to the burning of fireworks and bonfires.
- Acid rain continues to be a problem in the territory of Mexico City; however, environmental management has been ignored in the face of this problem and the situation in the other entities of the Megalopolis is unknown.

2.7.3. Recommendations to improve air quality monitoring in the Megalopolis

The recommendations presented below are intended to invite local and federal authorities to carry out a diagnosis of how the monitoring networks are operating and the quality of the data they are collecting. This will allow them to take the necessary actions to improve the performance of atmospheric monitoring in the Megalopolis region. The list of recommendations presented here is not exhaustive, but it does cover the major deficiencies found in air quality monitoring networks during the preparation of this document.

- ***Implement technical audits***. Carry out technical audits in each of the monitoring networks in order to identify the capacities and deficiencies during the different stages of the air quality monitoring process. The audits must be carried out with specialized personnel, preferably by independent third parties unrelated to the monitoring programs. Based on the results, establish realistic goals and work plans to guarantee continuous and permanent improvement of the proper operation in the short term.
- ***Implement quality control plans.*** Design and implement standardized harmonized plans for quality assurance and control in the different stages of monitoring, with the purpose of moving towards harmonization of the quality of the data generated throughout the region.

Establish appropriate quality metrics to evaluate the quality of the work carried out by the monitoring networks.

- ***Define objectives and validation metrics.*** Define objectives, criteria and metrics for data validation, prior to submission to SINAICA, as well as validation protocols prior to publication.
- ***Evaluate spatial repesentativeness***. Develop protocols for the evaluation of spatial representativeness and, based on them, carry out a review of the location and pollutants measured at all monitoring stations in the region. In those stations where their location compromises the monitoring objectives, carry out the necessary actions for their relocation, using harmonized protocols based on scientific evidence (for example, regional air quality models).
- ***Incorporate long-term financing mechanisms.*** Guarantee the sustainability of monitoring networks with appropriate budgets that include state, municipal and federal participation. Explore financing mechanisms, for example, trusts funds, as well as the participation of private resources, such as foundations, that allow the long-term operation of monitoring networks.
- ***Establish monitoring in non-urban areas.*** Consider the establishment of monitoring stations to cover spatial gaps, generate data on pollution levels in rural areas and in areas of ecological interest. Incorporate environmental justice criteria in the selection of monitoring sites.
- ***Retrospective validation of data.*** Based on the monitoring objectives, carry out a retrospective analysis of the data generated by the different monitoring systems and identify with appropriate flags those data of questionable quality.
- ***Strengthen the monitoring infrastructure.*** Through the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis, 150 million pesos were allocated to strengthen the monitoring infrastructure and prop up a Megalopolitan Air Quality Monitoring System. As of December 2022, the program presented a physical and financial progress of 94%. Although there is evidence of the equipment and infrastructure acquired, the presentation of clear and objective evidence of the benefits achieved in the improvement of monitoring, in the quality of the data, and in the dissemination of information by the financed entities is still pending.
- ***Expand technical capabilities.*** Carry out continuous training programs to increase the technical capabilities of the atmospheric monitoring networks personnel.
- ***Incorporate satellite measurements.*** The increasing availability of satellite data and a new generation of satellite air quality monitoring may provide scientists and policy makers with additional information on concentrations of criteria pollutants, which may be valuable for regions of the megalopolis outside the coverage of monitoring networks. However, satellite data will not replace surface monitoring, they are complementary. It is necessary to establish new stations and continue monitoring of ambient air quality on a routine basis with regulatory grade instruments in such areas.
- ***Incorporate calibrated and validated low-cost monitors.*** Recent developments in sensor technology have improved the performance of low-cost monitors and allow them to be used in particular conditions to complement current monitoring systems and create new

applications to better report the status of air quality. However, this will only be possible if a robust calibration and validation scheme is put in place to reduce uncertainties in the measurements.

- ***Public dissemination of information.*** It is important to maintain the permanent dissemination of the monitoring results to the population through the mass media, websites, applications and social networks.

ANNEX A
Emerging technologies to complement air quality monitoring

Despite the efforts undertaken in recent years by local and federal authorities to increase the coverage of atmospheric monitoring networks in the Megalopolis region, there is still a significant number of urban centers lacking information on air quality, while in suburban and rural regions the information is practically none (SEMARNAT, 2017). Among the main obstacles to the installation of new monitoring sites, we can cite the costs associated with acquisition, operation and maintenance of the monitoring equipment, the availability of miscellaneous services (for example, electrical power, communications, surveillance, etc.), lack of specialized personnel, and in some cases, lack of knowledge and/or interest of the local authorities.

Properly operated monitoring stations generate reliable and useful data for air quality management. To achieve this goal, federal regulation requires the use of equipment (and methodologies) with the designation of Reference Method or Equivalent Method, the data generated must undergo a strict validation process before being used in the evaluation of compliance with regulations and for management purposes. The goal is to obtain data of the highest quality and least uncertainty. In the following sections, we will refer to this equipment as regulatory grade.

The networks made up of stations equipped with regulatory-grade monitors can be complemented with measurements made with the so-called low-cost sensors and with satellite products, and thus solve the lack of information in regions where it is difficult to install a monitoring station, or do not have the resources to do so.

The low-cost sensors have attracted the attention of environmental authorities and researchers, as well as civil society organizations, educators, and people with some interest in air quality. However, it is important to highlight that, for management purposes, these devices are an exploratory tool and are in no way a substitute for regulatory-grade monitoring. When they are not used correctly, they could generate a bigger problem than the one they are intended to solve.

Regarding the use of satellite products by environmental agencies at an international level, it is still in an initial stage. Only agencies such as NASA of the United States and the Copernicus Atmospheric Monitoring Service (CAMS) of the Earth observation program, Copernicus, of the European Union, have made extensive use of satellite products as an integral part of air pollution prediction systems on a global scale.

A1. Low-cost Sensors

The term “low cost sensors” is commonly used to refer to devices that employ cheap sensors, the term “low cost” is derived from the acquisition cost, which is significantly less than that of regulatory grade equipment. These monitors are made up of sensors to measure particles and gases. The sensors use known technologies, for example, in the case of particles, they use optical counters, while for gases, electrochemical or metal oxide sensors are usually used .(Lewis et al., 2018; WMO 2021). Generally, these are compact, lightweight equipment that is easy to deploy and has low energy consumption. Their installation requires minimal training on the part of the operator and minimal maintenance is required.

Although the cost of one of these sensor systems is considerably less than that of a regulatory-grade monitor, it is necessary to take into consideration the costs of the acquisition and those derived from operation, including power, data processing, calibration and data quality assurance. In some cases, it is necessary to cover a periodic fee to access the data and make use of the visualization and analysis platforms.

In terms of performance, low-cost sensors tend to be less sensitive, have poor reproducibility in field measurements and can be affected by variations in temperature and humidity. Gas sensors may respond to more than one pollutant depending on the mixture of pollutants present, while particle sensors may encounter interferences caused by variations in the size distribution and the optical properties of aerosols (Lewis et al., 2018; WMO, 2021). Sensor performance often varies from site to site, therefore their use in areas or regions with different microclimates and microenvironments can be problematic. In addition, it should be considered that they have a short lifespan (from months to 1-3 years),

It is possible to increase the quality of data from low-cost sensors by applying operation and maintenance protocols, developing methodologies for calibration and quality assurance, developing algorithms to compensate for uncertainties in measurements, and applying effective strategies for data validation (WMO, 2021). There are protocols developed by research institutes and national standardization institutes. For example, the United States EPA conducts and sponsors various projects for the development, evaluation, and application of these devices and has published standard protocols for the evaluation of the performance of O_3 and $PM_{2.5}$ sensors in ambient air to systematize their evaluation, simplify the presentation of the results, and support consumers in the selection of the appropriate sensors for their application. The information is available on their Air Sensor Toolbox website (US EPA, n.d.). These actions can significantly improve data quality, but they also increase operating costs, and under certain circumstances, could equal or exceed the costs of operating regulatory monitoring. Nevertheless, despite these efforts, some residual uncertainties remain.

In Mexico City, SEDEMA, with the support of the ICyCC-UNAM, carried out a project whose main objectives were (1) the evaluation of the performance of different commercial devices and prototypes by comparing them with regulatory grade equipment, and (2) the deployment of pilot networks for monitoring $PM_{2.5}$ and CO_2. The results showed a relatively consistent performance for $PM_{2.5}$ measurement among the different devices evaluated and good agreement with the reference equipment. In the case of sensors for PM_{10} and gases, a greater disparity in performance was observed. In addition, evidence of a difference in response was found when the sensors are used at two sites with different environmental conditions in Mexico City. The exercises on the deployment of $PM_{2.5}$ and CO_2 networks showed the potential of low-cost devices to generate useful data for various applications, as well as the challenges behind the installation of operational networks with low-cost devices in urban environments. The most important products of this project was the development of recommendations and guides in Spanish for the selection, evaluation and use of these technologies. The results are available on the website (Grutter et al., 2023).

A2. Satellite products

Electromagnetic radiation (EMR) emitted by the sun is absorbed, re-emitted, reflected and scattered by the Earth and its atmosphere; most instruments installed on satellite platforms derive air quality data indirectly by detecting this radiation. It is currently possible to identify several pollutants of interest from space, including formaldehyde (HCHO), ammonia (NH_3), CO_2, NO_2, SO_2, CO and $PM_{2.5}$ (inferred from aerosol optical depth). It is also possible to detect O_3; however, it is still a challenge to distinguish surface O_3 from stratospheric O_3 (Duncan et al., 2014).

Satellites provide data with wide spatial coverage. Those in polar orbit (which move from pole to pole) collect data from any geographic location once a day as the Earth rotates. While those in geosynchronous orbit (which have an orbit in which the satellite's movement coincides with the Earth's rotation) continuously collect data for a specific region of the planet. These measurements are not without difficulties. The satellite measurements correspond to the sum of the species present within the column that is under the sensor's observation zone, not the concentrations at surface level, which are the ones of most interest to environmental management. Sometimes the spatial resolution is not sufficient to appreciate the spatial and temporal gradients of pollutants, mainly those of short life, or to identify specific sources within the urban scale. Also, the presence of cloudiness can limit the observation and detection of contaminants present near the ground. Polar-orbiting satellites provide observations for a specific time of day. However, biases in spatial observations can be corrected in combination with atmospheric models (Lamsal et al., 2018) and surface observations.

Various satellite instruments are currently in orbit that can provide useful data for the study of air quality (Dutta et al., 2021; NASA, 2022). Some have adequate spatial and temporal resolutions for urban pollution assessment, such as the European Space Agency's TROPOMI (TROPOspheric Monitoring Instrument), which collects data on NO_2, SO_2, CO and CH_4 at suburban-scale spatial resolution. (Veefkind et al., 2012).

With the arrival of geosynchronous orbit satellites, it will be possible to obtain data with unprecedented spatial and temporal resolutions (Judd et al., 2018; CEOS, 2019). For Mexico and in particular for the region of the Megalopolis, the TEMPO satellite of NASA, whose launch is scheduled in 2023, will carry out measurements in North America, bringing great benefits to cover the lack of information on air quality in large part of the country's territory. The TEMPO instrument is a grating spectrometer, sensitive to visible and ultraviolet light wavelengths (Chance et al., 2013). By measuring sunlight reflected and scattered from the Earth's surface and atmosphere to the instrument's detectors, TEMPO's UV and visible light sensors will provide spectra of O_3, NO_2, CO, CH_4, and other species important in daily atmospheric chemical cycles. TEMPO will contribute to assess pollution at peak times in urban and suburban areas, pollution transportation from biomass burning and O_3 production, pollution emitted from oil and gas fields, pollution footprints from ships and plumes from drilling platforms.

Although it is possible to use satellite data to assess changes in air quality from one year to the next, the most important challenges are in linking it with data from surface monitors (Holloway et al., 2021). Combining data from surface monitors, satellites, and modeling can significantly improve spatial coverage and provide continuous data sets in space and time.

Satellite instruments do not measure suspended particles directly, but rather infer their concentration from optical depth measurements and data from surface monitoring or obtained through numerical models. However, satellite estimates of $PM_{2.5}$ have become one of the most important tools for health assessment and other applications (Holloway et al., 2021). The use of data from regulatory-grade stations and low-cost sensors can significantly improve the accuracy and robustness of satellite estimates of $PM_{2.5}$ at the surface (Malings et al., 2020; de Souza et al., 2020; Li et al., 2020). The results from some studies have shown the value of these estimates for evaluating air quality and the effects of $PM_{2.5}$ on human health (Holloway et al., 2020; Malings et al., 2020; Lin et al., 2020).

ANNEX B

Time series for daily averages of pollutants measured in the monitoring systems of Hidalgo, Puebla, and Querétaro

The graphs shown in this section are prepared by the authors using data from the National Air Quality System (SINAICA), available at https://sinaica.inecc.gob.mx (accessed on July 25, 2022).

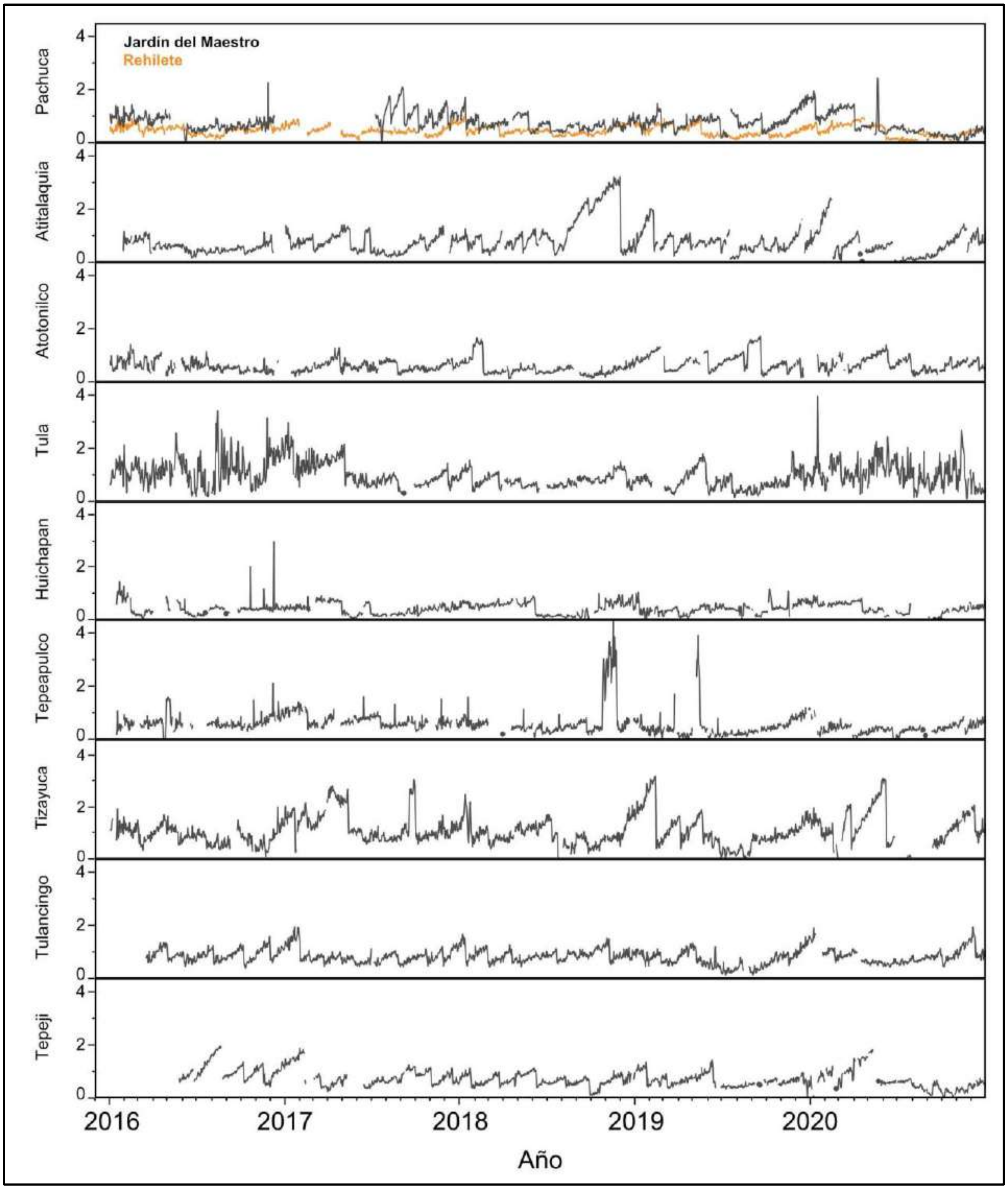


Figure AB-1. Time series of the daily averages of carbon monoxide in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of parts per million (ppm).

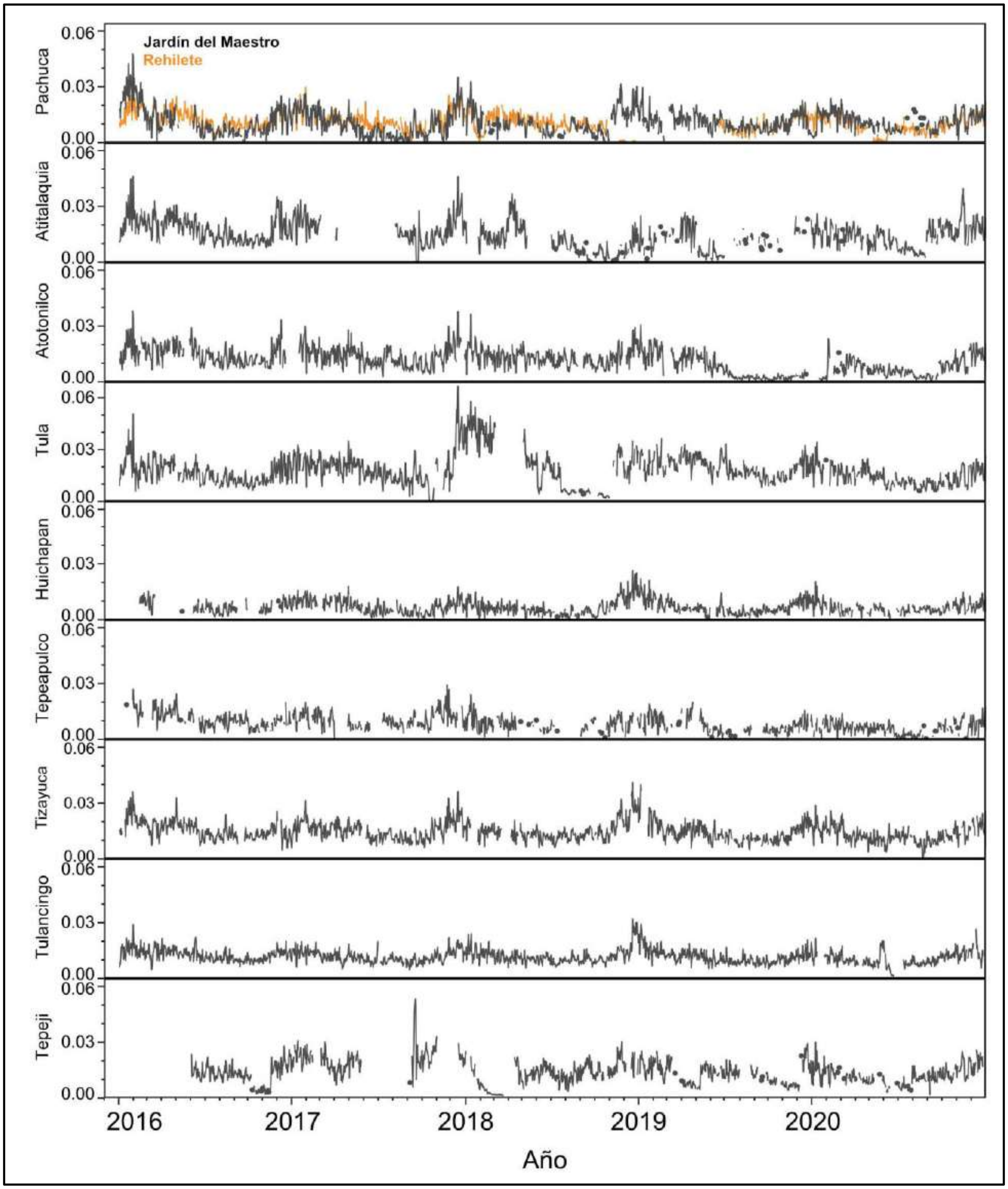


Figure AB-2. Time series of the daily averages of nitrogen dioxide in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of parts per million (ppm).

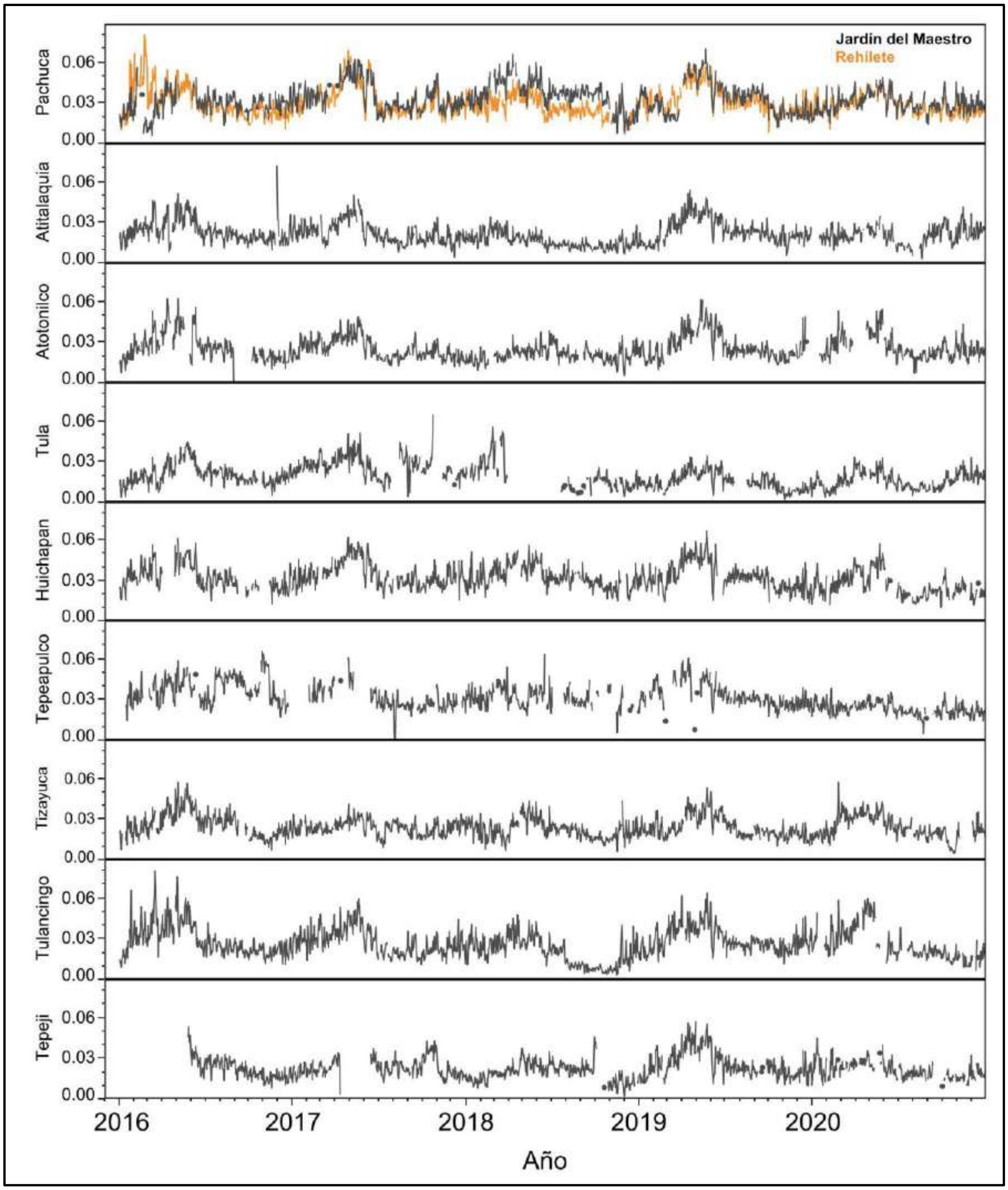


Figure AB-3. Time series of the daily ozone averages in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of parts per million (ppm).

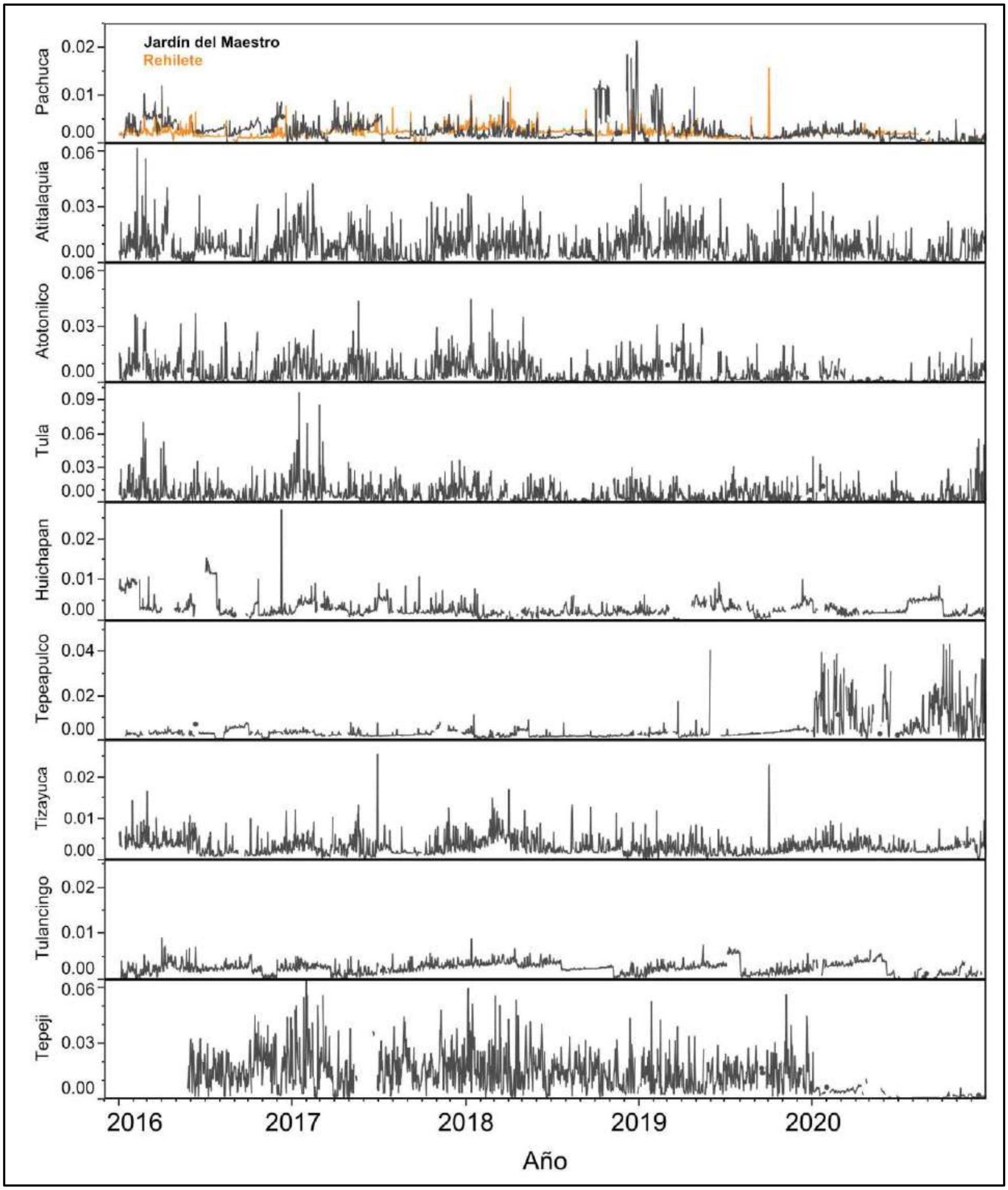


Figure AB-4. Time series of the daily averages of sulfur dioxide in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of parts per million (ppm).

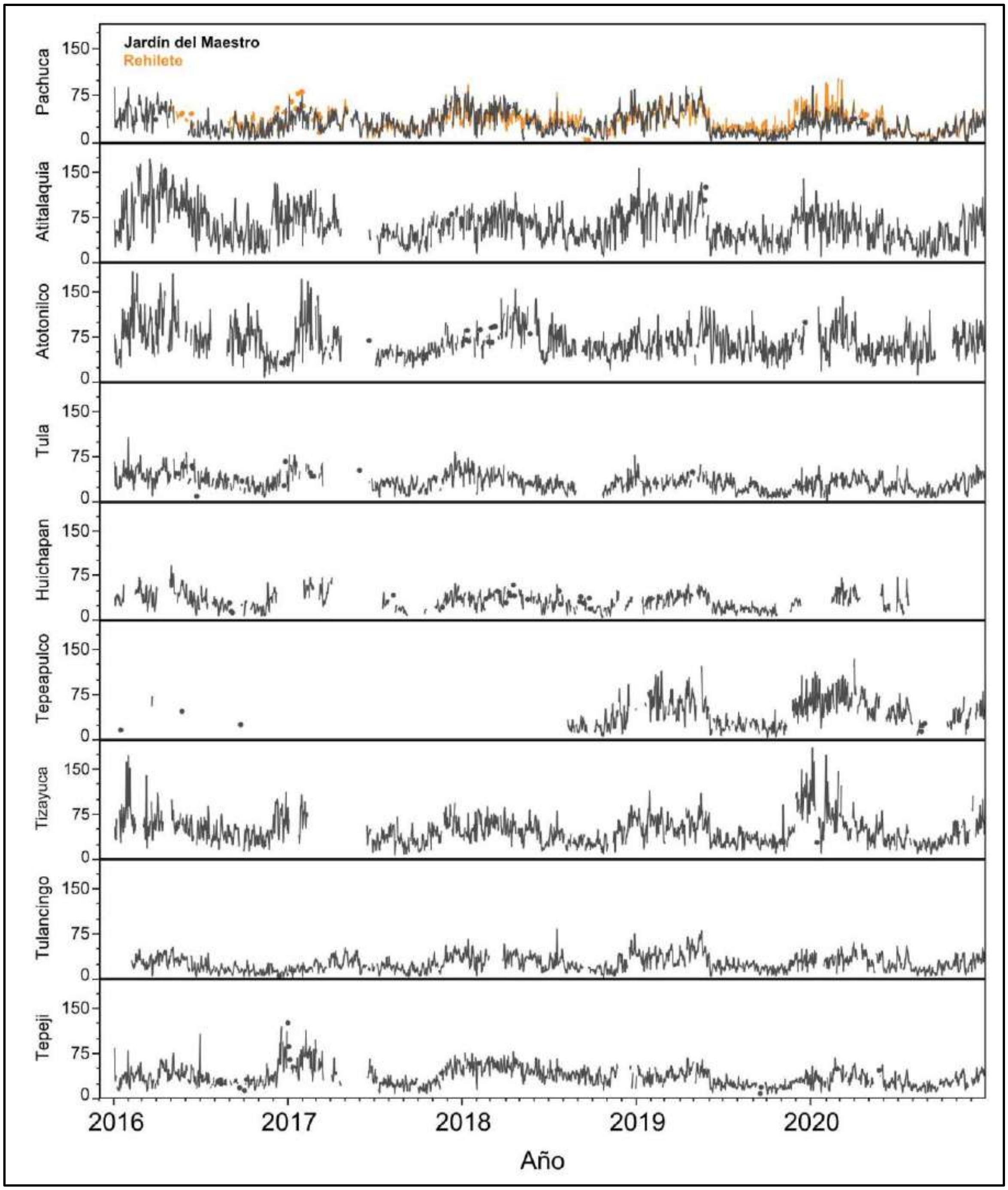


Figure AB-5. Time series of the daily averages of PM10 in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of micrograms per cubic meter (µg/m^3).

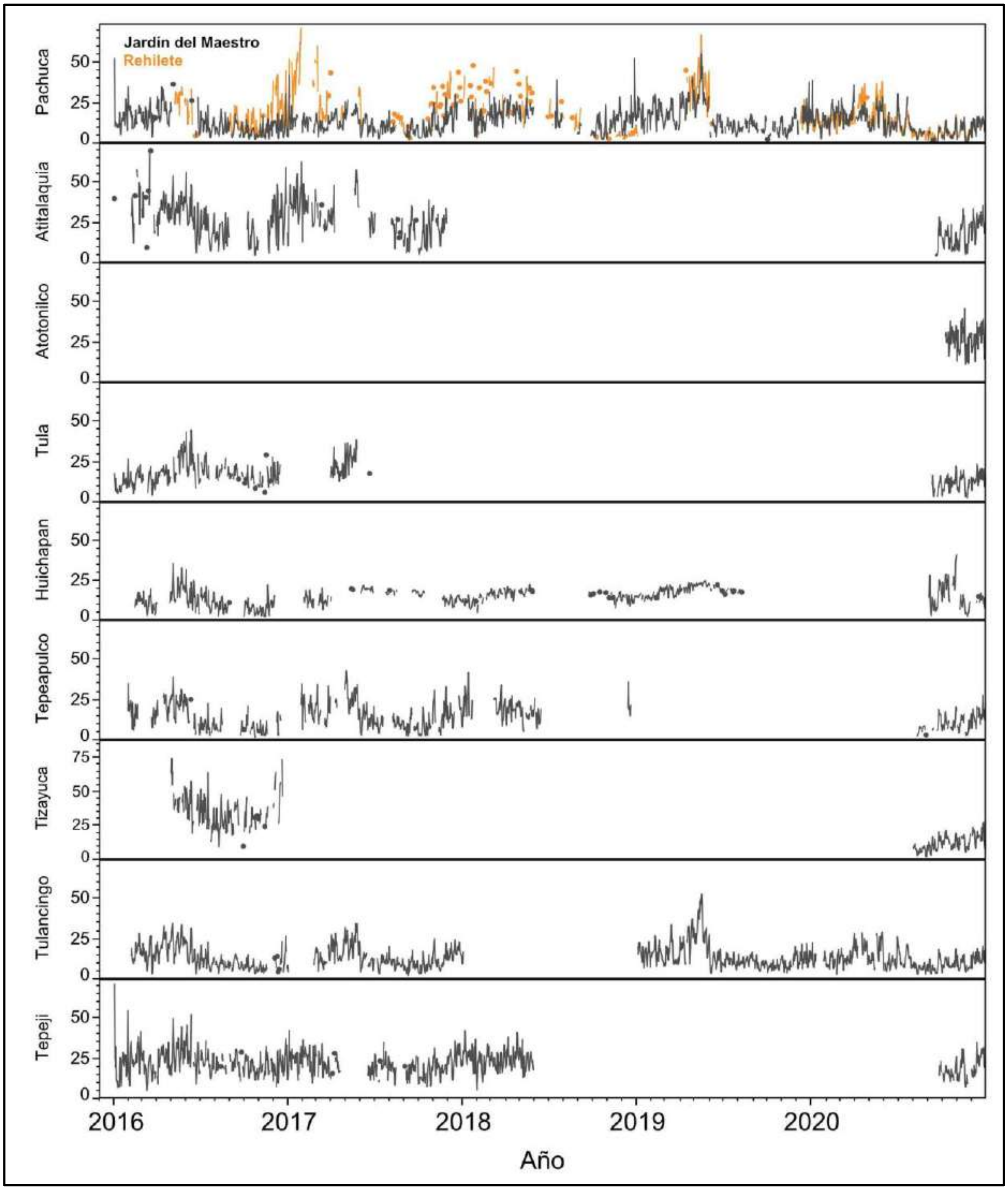


Figure AB-6. Time series of the daily averages of PM2.5 in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of micrograms per cubic meter (µg/m^3).

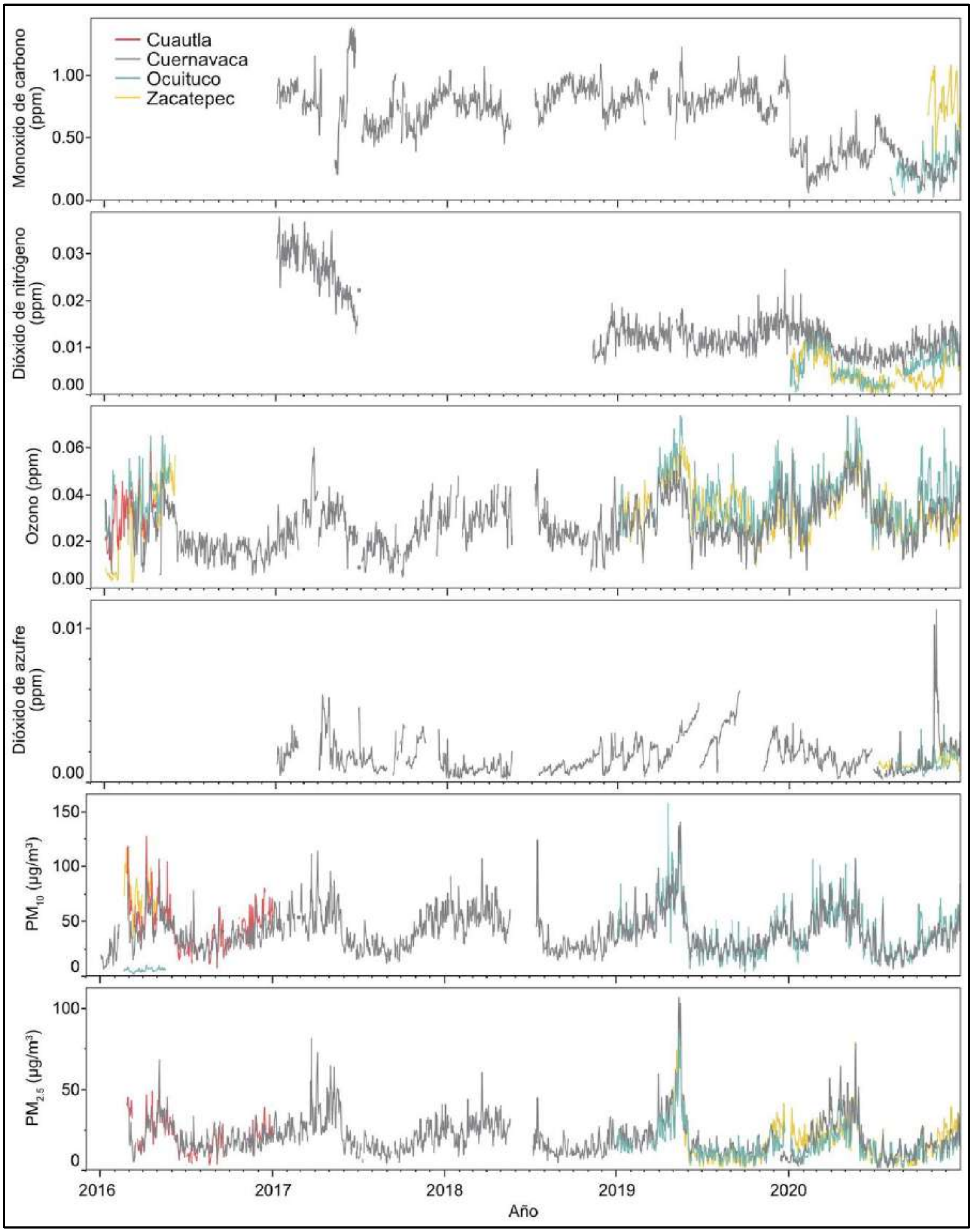


Figure AB-7. Time series of the daily averages of PM10 in each of the locations in the state of Hidalgo where continuous monitoring was carried out during 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are in units of micrograms per cubic meter (µg/m^3).

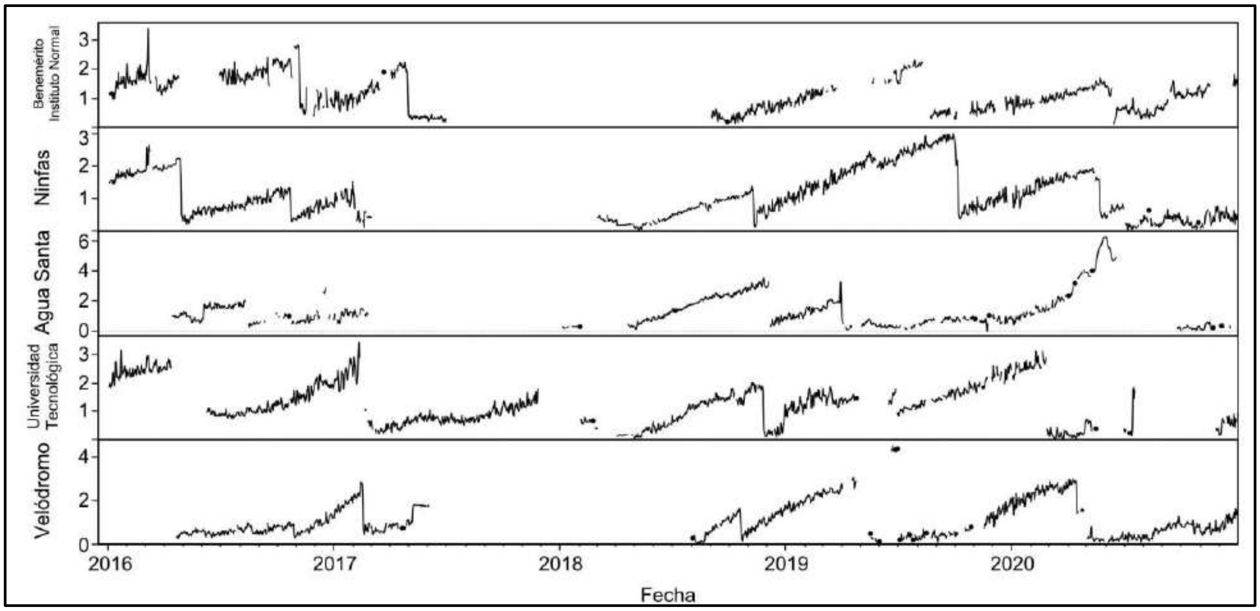


Figure AB-8. Time series of the daily averages of carbon monoxide in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

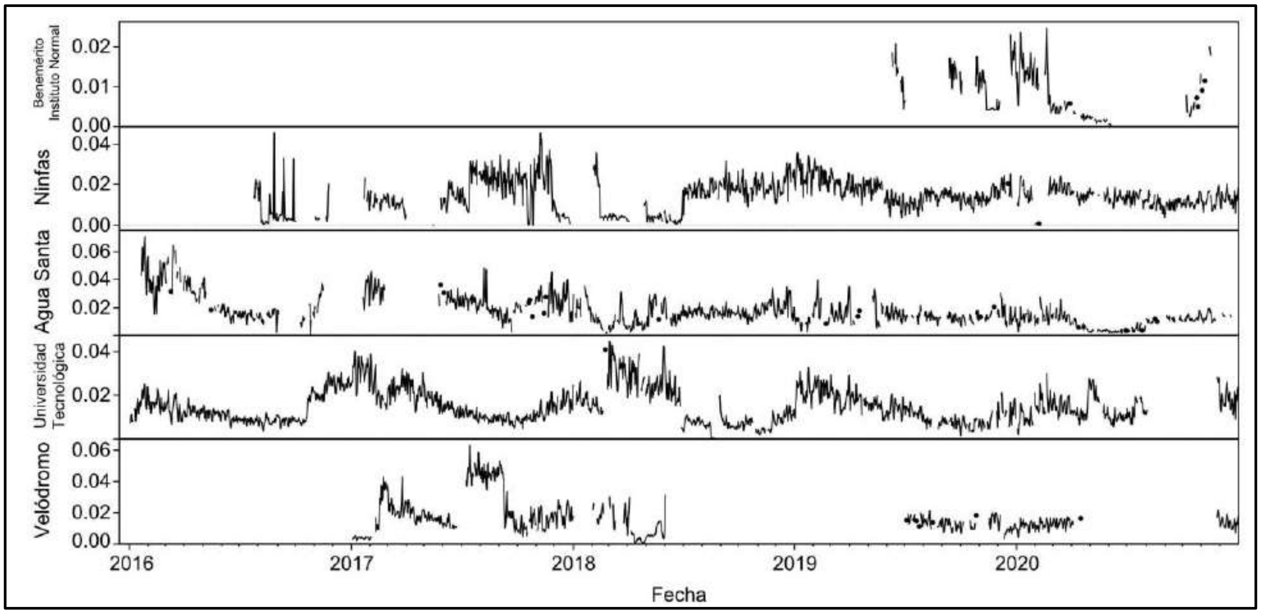


Figure AB-9. Time series of the daily averages of nitrogen dioxide in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

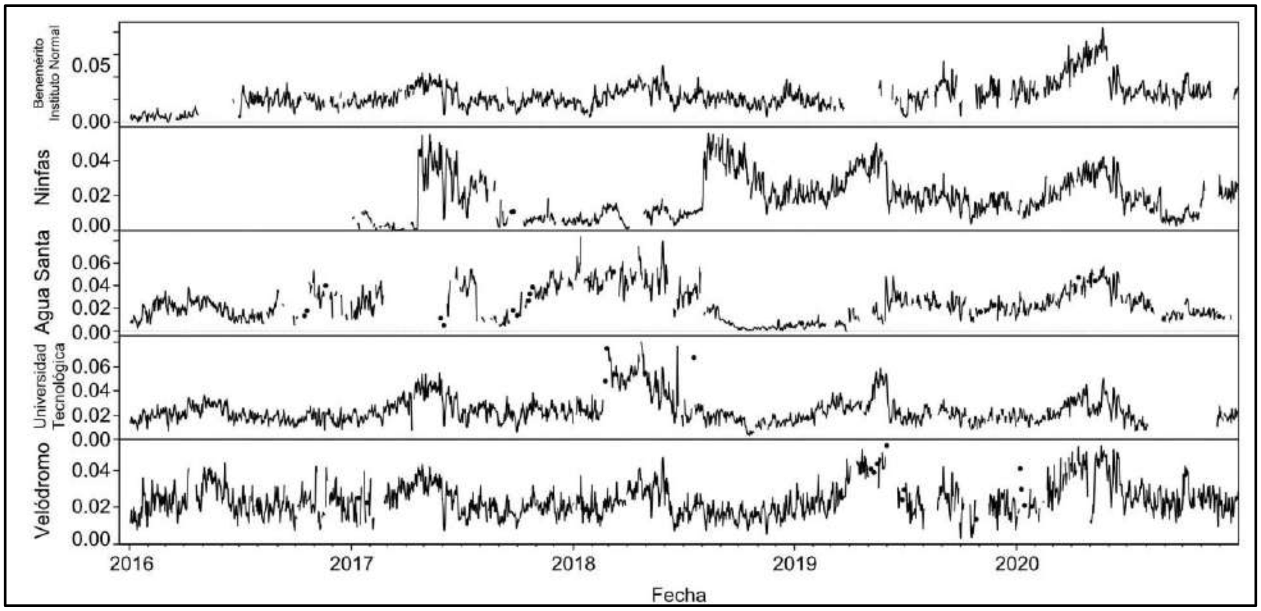


Figure AB-10. Time series of the daily ozone averages in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

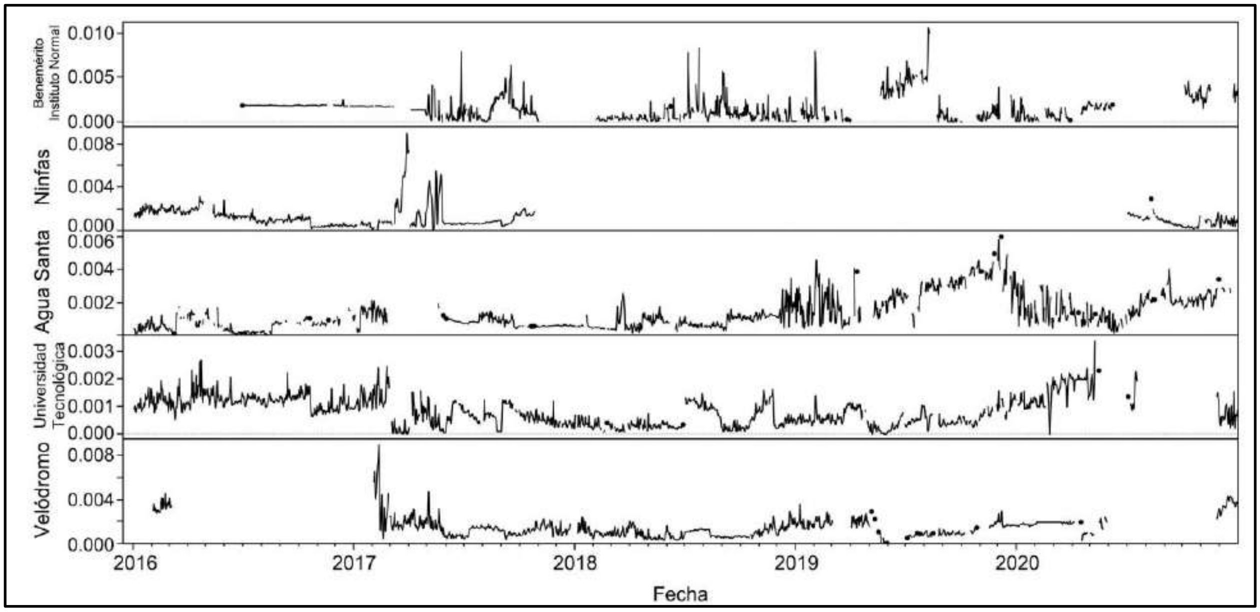


Figure AB-11. Time series of the daily averages of sulfur dioxide in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

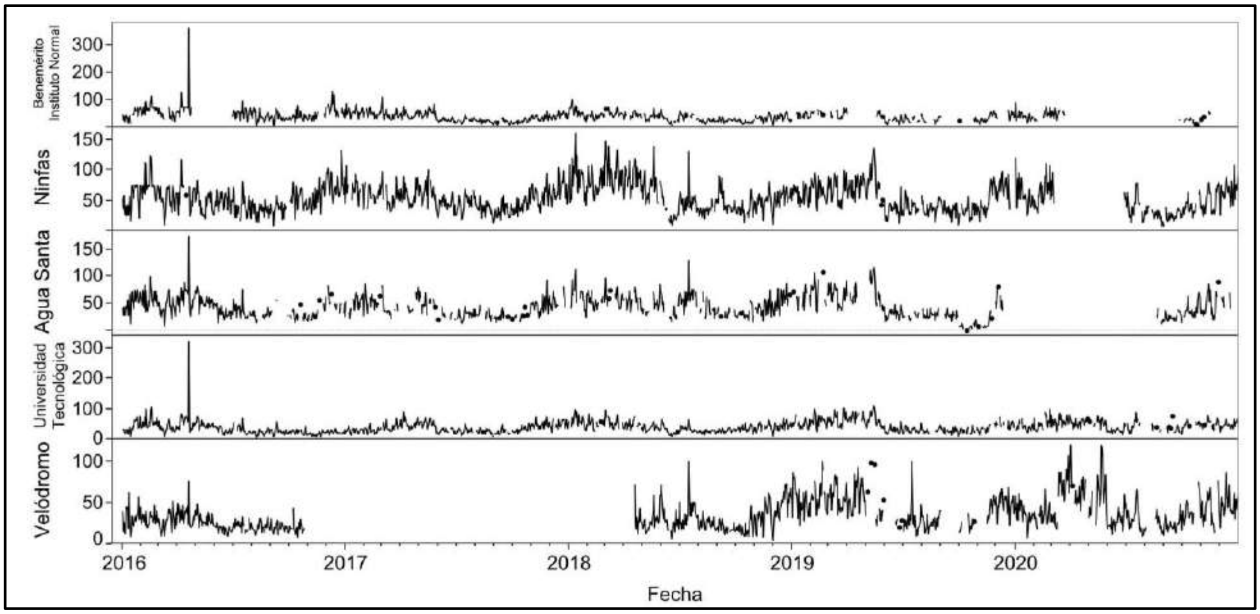
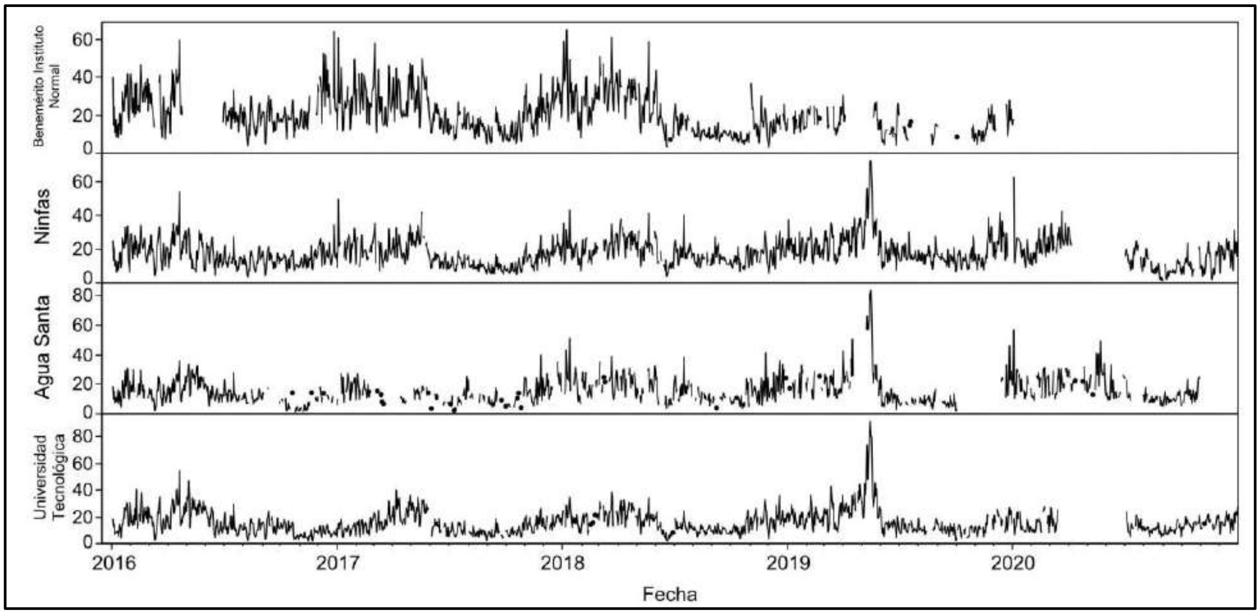


Figure AB-12. Time series of the daily averages of PM_{10} in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in micrograms per cubic meter (µg/m^3).



FigureAB-13. Time series of the daily averages of $PM_{2.5}$ in the stations of the state of Puebla during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in micrograms per cubic meter (µg/m^3).

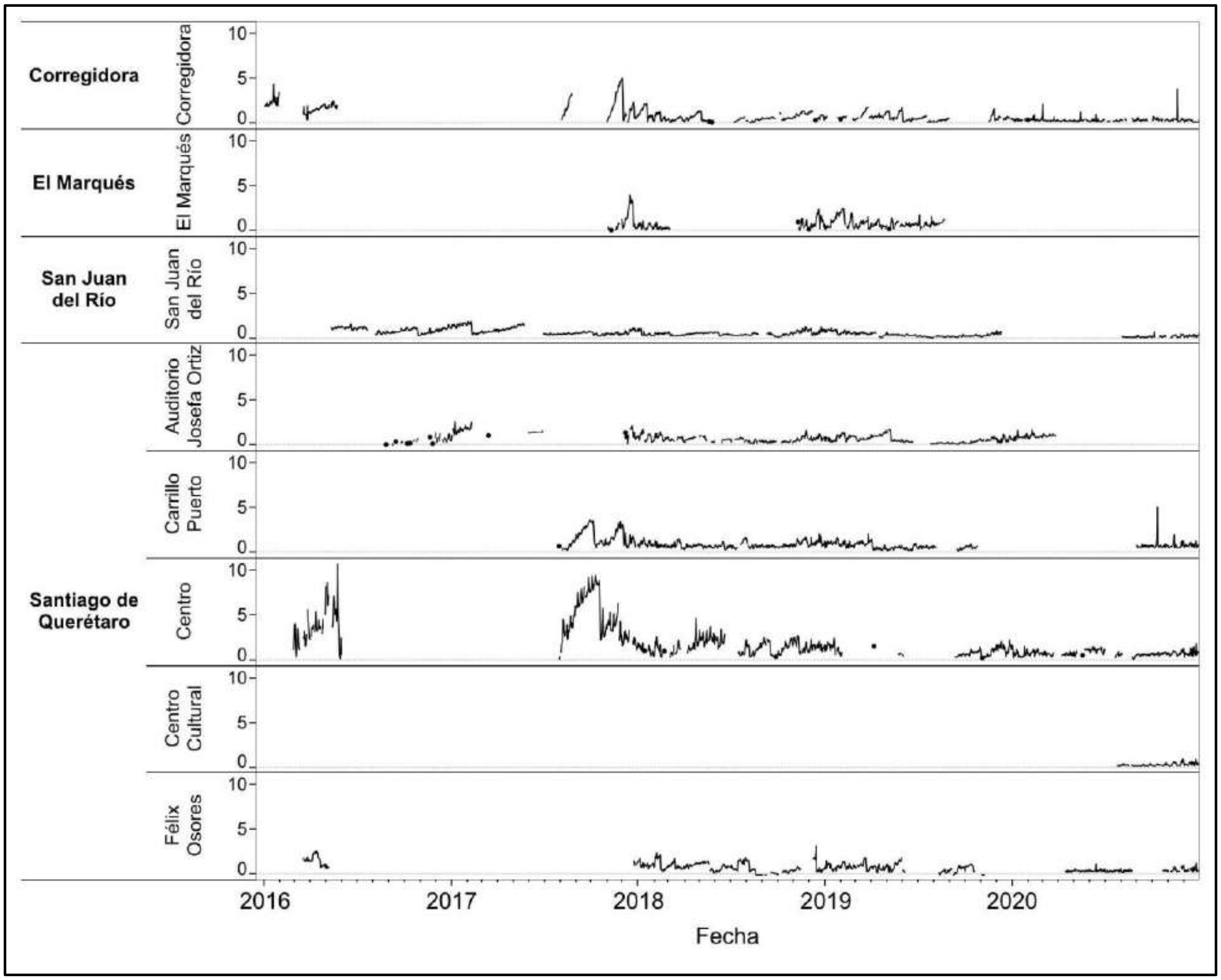


Figure AB-14. Time series of the daily averages of carbon monoxide in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm)

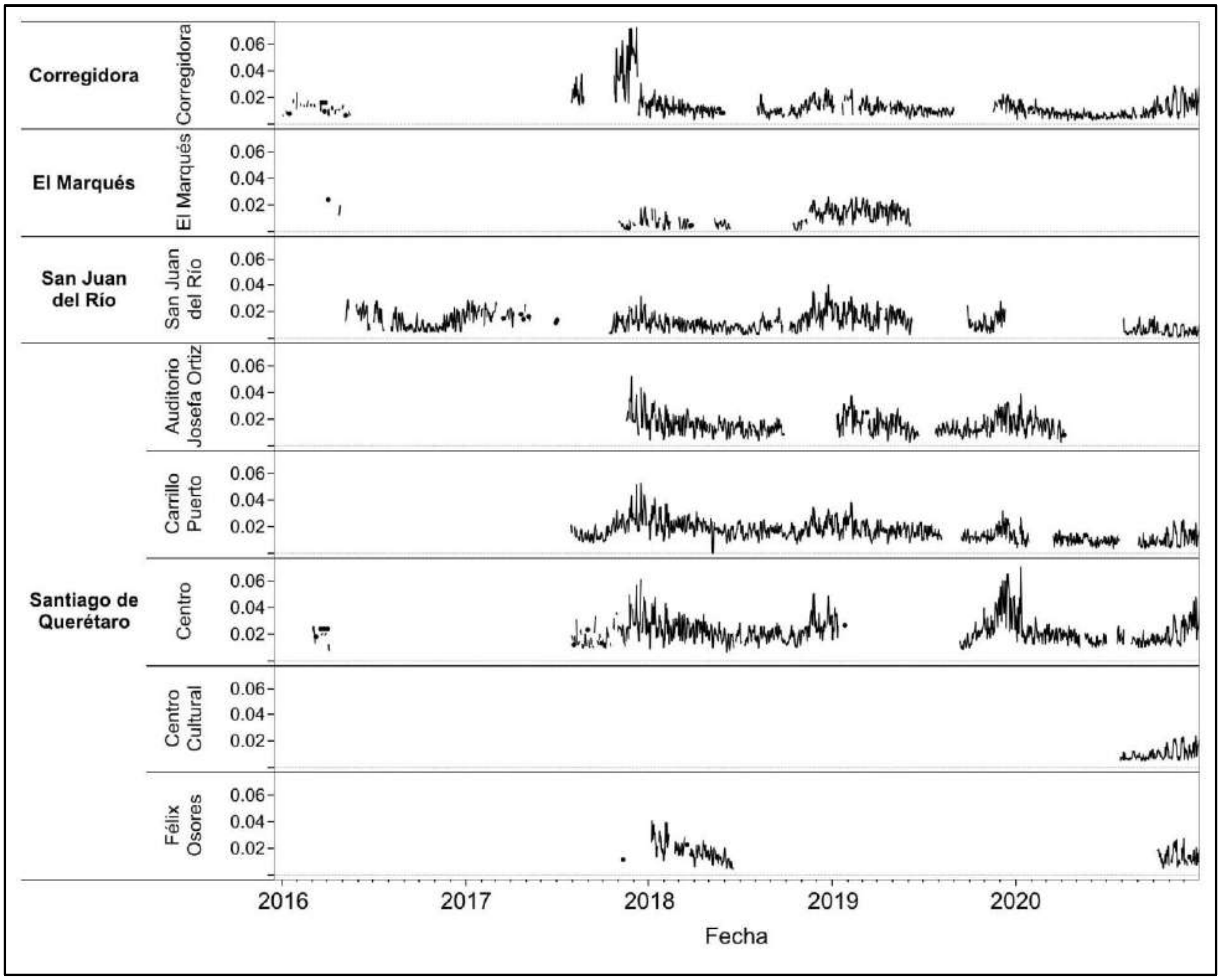


Figure AB-15. Time series of the daily averages of nitrogen dioxide in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

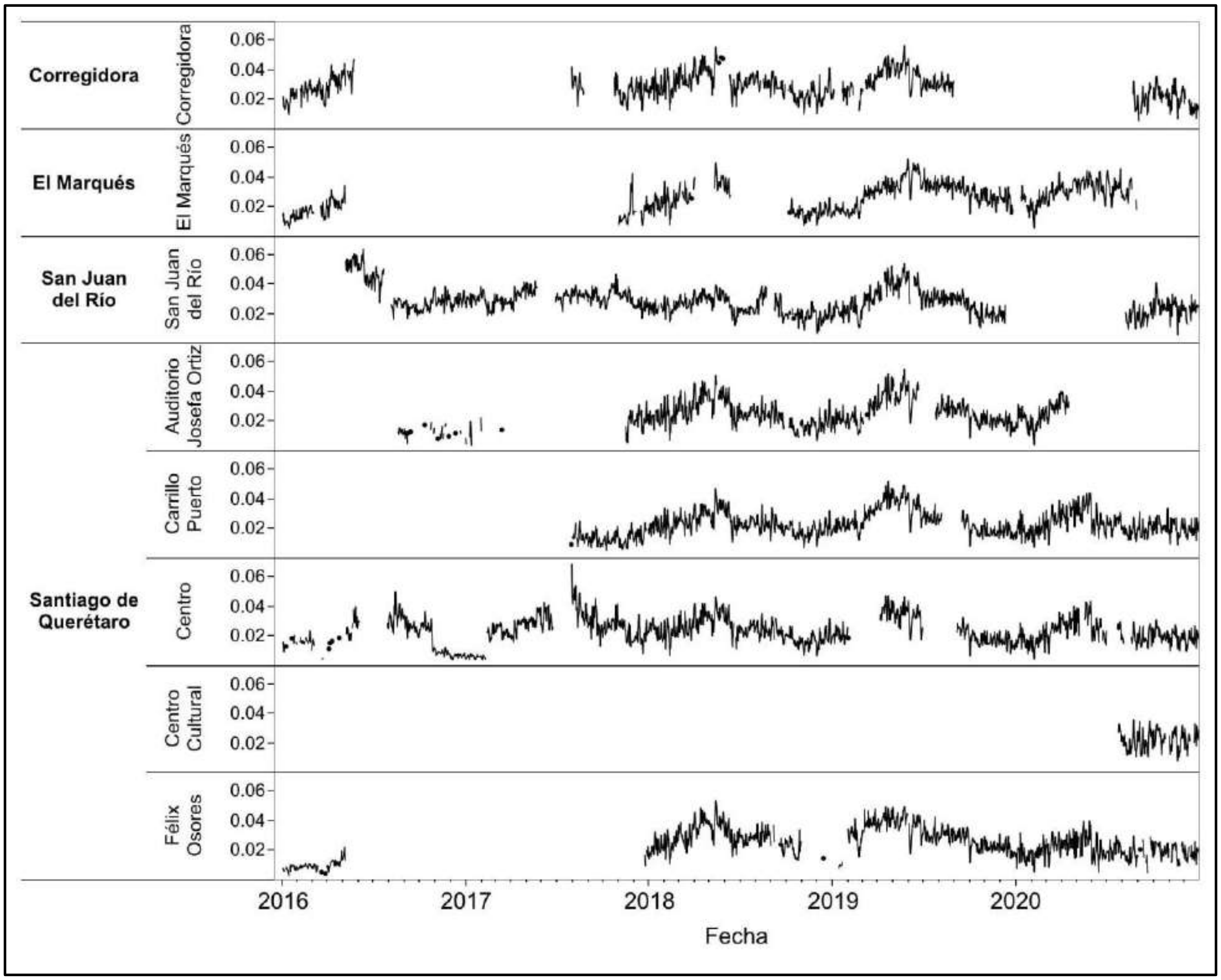


Figure AB-16. Time series of the daily ozone averages in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

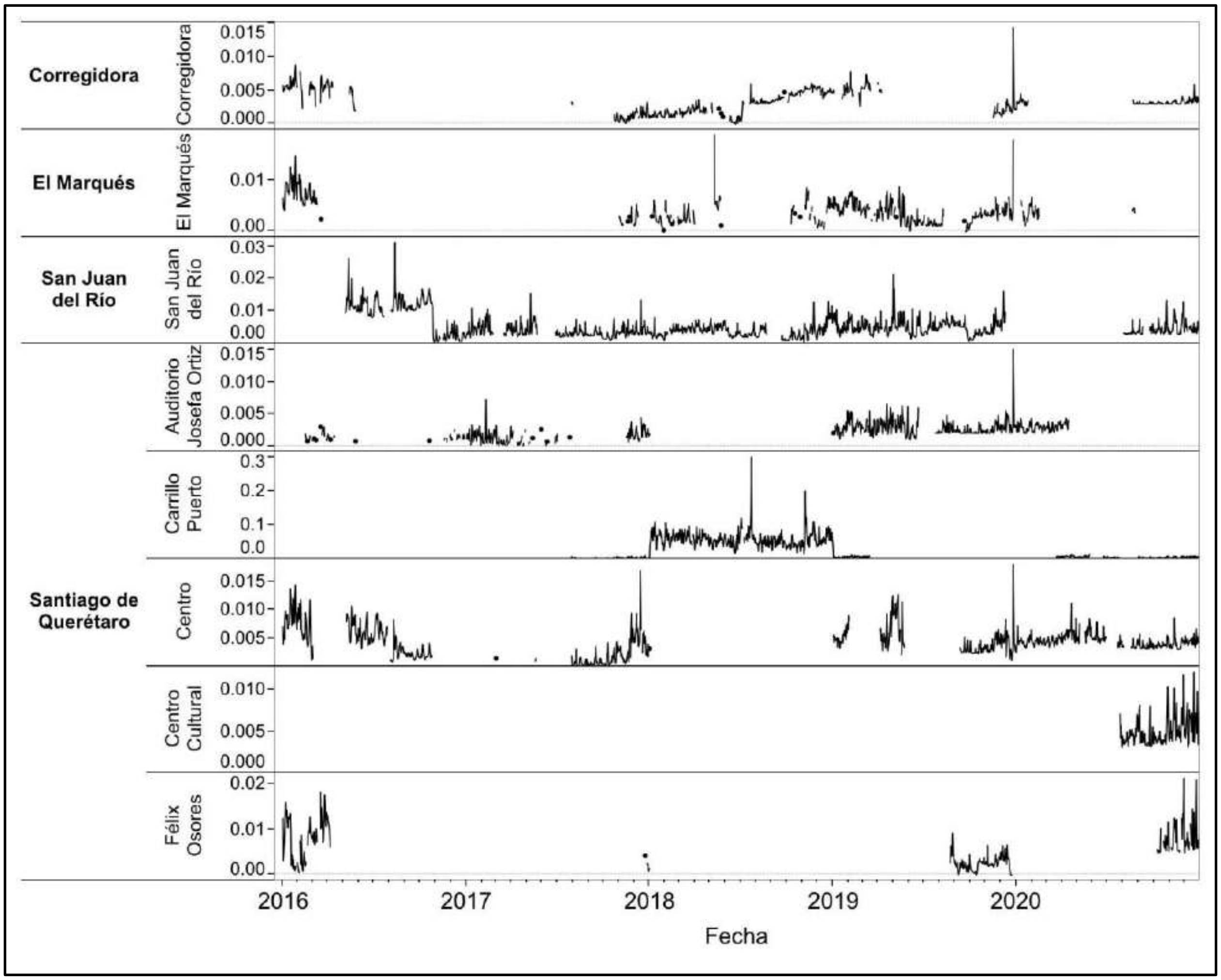


Figure AB-17. Time series of the daily averages of sulfur dioxide in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in parts per million (ppm).

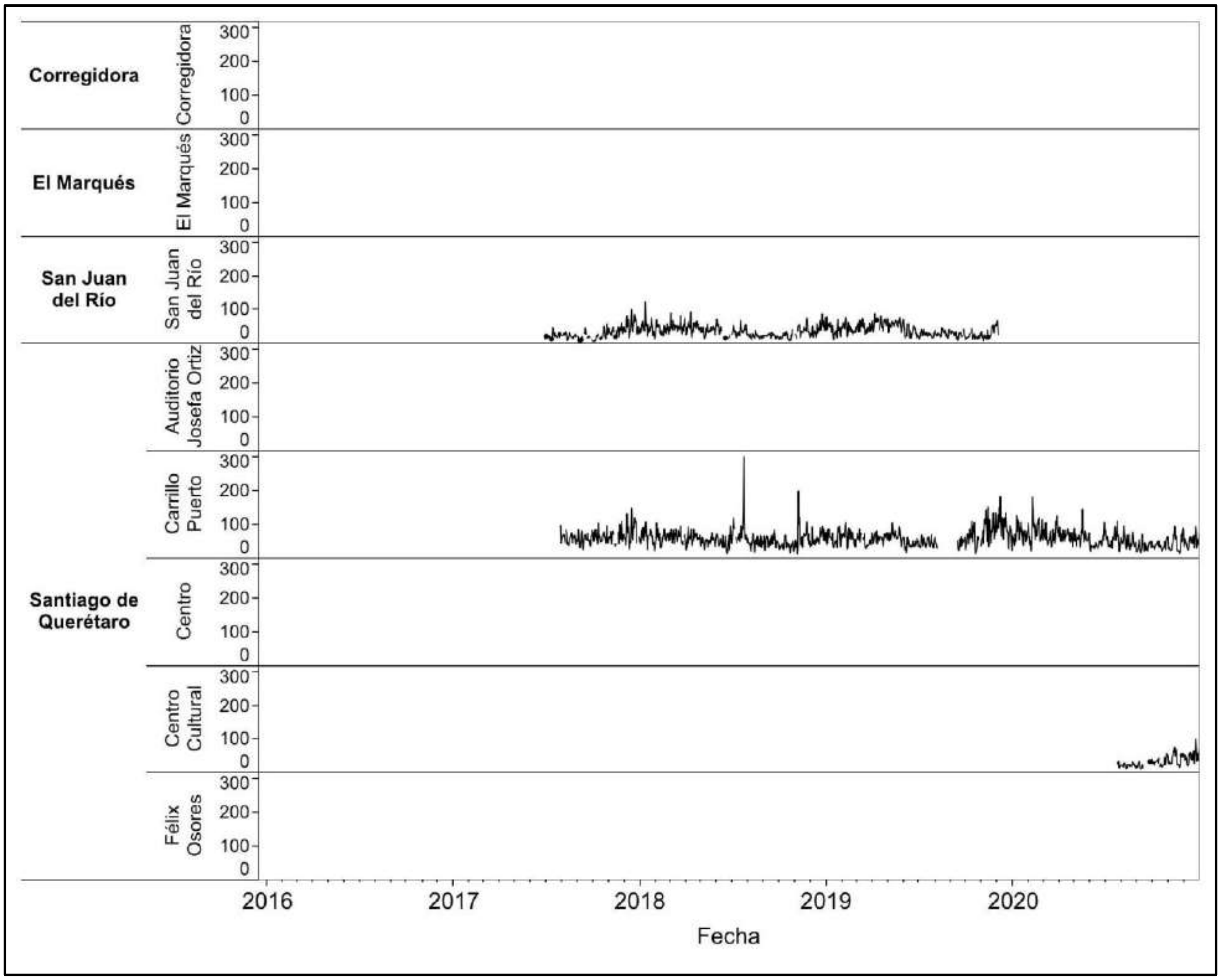


Figure AB-18. Time series of the daily averages of PM_{10} in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in micrograms per cubic meter (µg/m^3).

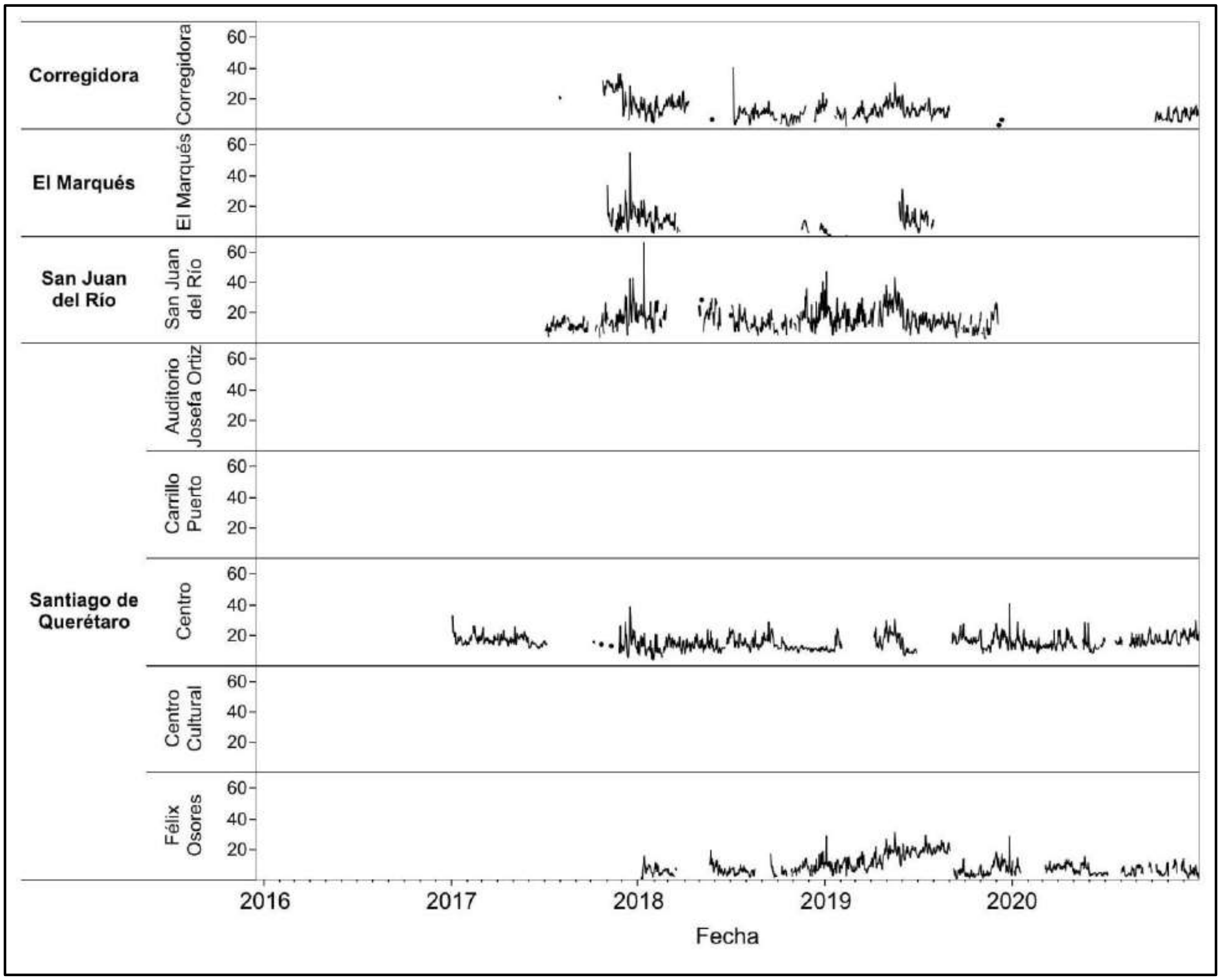


Figure AB-19. Time series of the daily averages of $PM_{2.5}$ in the stations of the state of Querétaro during the period 2016-2020. The daily averages were calculated using the validated hourly data available in SINAICA, considering a minimum requirement of 75% valid data for the calculation. Concentrations are expressed in micrograms per cubic meter (µg/m^3).

CHAPTER 3. ATMOSPHERIC POLLUTANT EMISSIONS IN THE MEGALOPOLIS

3.1. Development of emission inventories in the Megalopolis

The deterioration of air quality as a result of the emission of atmospheric pollutants in the Megalopolis is a growing problem due to its severe impacts on the environment and on the health of the population. There is also national and international interest in controlling air pollution and reducing the impacts of climate change by reducing, managing, and controlling emissions from sources in key sectors. Furthermore, air pollution also causes high economic costs and severe social impacts derived from its large effects on mortality and morbidity, deteriorating the quality of life of the population. It is therefore essential to identify the origin of the sources and the characteristics of the emissions of primary pollutants, particularly those that are precursors of secondary compounds that can be highly toxic and persistent and affect public health.

Identifying and characterizing emissions should be the first step in designing air pollution prevention and control programs. Furthermore, information on emissions must be periodically reviewed and updated as part of the processes for evaluating the effectiveness of control programs. One of the priority lines of action within the control programs in urban areas consists of the development of technical tools for the formulation of strategies to reduce polluting emissions, through the preparation of inventories of polluting emissions into the atmosphere. In any case, emission inventories are essential instruments in air quality management processes and in decision-making, since they are the starting point and an essential tool for the design, implementation, and evaluation of programs to improve air quality.

At its most basic level, an emissions inventory is a set of databases that identify, characterize, and describe emissions of air pollutants according to the type of emitting source, the chemical composition and the amounts of pollutants emitted in a geographic area and a certain time interval (US EPA, 1999). However, emissions inventories can also become sophisticated tools consisting of dynamic databases used to represent the complex speciation of chemical compounds and the high spatial resolution (meters to 1 km) and temporal (1 hour to several days) distributions of the emitting sources. The level of sophistication of an inventory is related to the objectives for its use, the technical, infrastructure, and time resources used for its preparation, and the degree of acceptable uncertainty that is desired to be used.

In principle, emission inventories are developed following disaggregated ("bottom-up") or aggregated ("top-down") estimation methods that use information from emission factors, activity data, and results of emission models. However, in practice, inventories are compiled using a combination of both methods depending on the information available, the objectives of the inventory, and the levels of uncertainty in which it is decided to prepare the estimates.

In general, the inventory of estimated emissions of criteria pollutants and other air pollutants are grouped under four categories according to their sources of emissions: i) Mobile sources: on-road vehicles such as passenger cars, commercial buses and trucks, motorcycles; non-road vehicles such as aircraft, marine vessels, construction and agricultural equipment; ii) Point or Stationary sources: Fixed location facilities such as factories, refineries, boilers and power plants; iii) Area sources: Small-scale industrial, commercial and service operations; municipal solid waste facilities and landfills; wastewater treatment plants; consumer products; residential heating/cooling and fuel use; construction activities; agricultural activities and confined animal feeding operations; unpaved roads; and iv) Natural sources: such as vegetation, wind-blown dust, volcanoes, forest fires, and sea salt spray.

Emission inventories provide essential input data for atmospheric chemical transport models, which are described in Chapter 4. Uncertainties in the emission sources are an important factor in determining the accuracy of the simulations and forecasts obtained from the models; therefore, these emissions uncertainties can have large impacts on the design of control strategies.

This section presents a summary of the current state of knowledge regarding the development of emission inventories relevant to the Megalopolis, the lessons learned, and the main challenges to improve knowledge of emissions in the region.

3.2. Mexico national emissions inventory

Along with the introduction of the first air pollutant monitoring stations in Mexico, the initial efforts to improve air quality in the 1990's also included the first actions to estimate air pollutants such as total suspended particles (TSP), nitrogen oxides (NO_x) and sulfur dioxide (SO_2). It is important to note that the first efforts to characterize the emission sources through an inventory were intended to respond to major social demands to reduce emissions due to the evident deterioration of air quality in the metropolitan area of Mexico City. In particular, the environmental authorities of Mexico City at that time began to estimate the emissions from the city's main emitting sources, including some relevant area sources, mobile sources from gasoline and diesel vehicles, and some of the main federal industrial sources (large emitters). The information obtained was useful to define the first actions to control pollution in Mexico City (Molina et al., 2002).

At the federal level, the first National Emissions Inventory of Mexico (INEM) was created for the base year of 1999 as a result of the working group of the General Directorate of Air Quality Management and Pollutant Emissions and Transfer Registry (DGGCARETC, *Dirección General de Gestión de la Calidad del Aire y Registro de Emisiones y Transferencia de Contaminantes*) of the Ministry of the Environment and Natural Resources (SEMARNAT, *Secretaría de Medio Ambiente y Recursos Naturales*). Recently, DGGCARETC was replaced by the General Directorate for Industry, Clean Energies and Air Quality Management (*Dirección General de Industria*, *Energías Limpias y Gestión de la Calidad del Aire*, DGIELGCA) and is responsible for preparing the inventory. The INEM includes information on the emissions of the pollutants: carbon monoxide (CO), NO_x, sulfur oxides (SO_x) and particles with an aerodynamic diameter of less than 10 and 2.5 micrometers (PM_{10} and $PM_{2.5}$ respectively), volatile organic compounds (VOC) and ammonia (NH_3) emitted by the main anthropogenic and biogenic sources (https://www.gob.mx/semarnat/documentos/documentos-del-inventario-nacional-de-emisiones, accessed November 26, 2022). The INEM also includes the estimation of black carbon (BC) and greenhouse gas (GHG) emissions but using methodologies that are not from the Intergovernmental Panel on Climate Change (IPCC).

In the preparation of the INEM, the SEMARNAT working group has traditionally collaborated with other entities dependent on the Federal Government and environmental authorities of the states and municipalities, as well as with academic, research, and non-governmental organizations. Subsequent INEM estimates have been made for the base years 2005, 2008, 2011, 2013, 2014, and 2016, seeking in each version to improve the accuracy of the information obtained by updating the emission models, emission factors, and activity data. In turn, each version of the INEM has made it possible to maintain the technical capacity of specialized personnel at the federal level in generating the inventory by incorporating the experience of personnel from other government agencies. SEMARNAT generates the guides, guidelines and general directives to estimate the inventories of the majority of the entities of the country. However, it is important that the experience gained in the preparation of emissions inventories is also transferred to the technical staff of other states and municipalities in the country.

At the Megalopolis level, it is necessary to increase the spatial and temporal resolution of the emissions inventory, as well as the chemical speciation of the VOCs and suspended particulate matter (PM) profiles and include emerging sources of pollution. Currently, only Mexico City has an emissions inventory with adequate spatial and temporal resolution suitable for modeling for the entire entity, and maintains a continuous effort to identify and quantify new emission sources, considering the use of observations in estimating emission profiles and their temporal variability. Other significant challenges in the preparation of the INEM include the availability of activity data, the updating of emission factors determined at the regional level for local use, and the availability of technical personnel in the entities to prepare the inventories and keep them updated, as well as preserve data traceability and improve the estimation of uncertainties.

In addition to the INEM, the National Institute of Ecology and Climate Change (INECC, *Instituto Nacional de Ecología y Cambio Climático*) is responsible for developing the National Inventory of Emissions of Greenhouse Gases and Compounds (INEGYCEI, *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*) as stated in the General Law on Climate Change (LGCC, *Ley General de Cambio Climático*) (INECC, 2021). The INEGYCEI is an essential environmental management tool for developing policies related to mitigating climate change and also the international commitments that Mexico presented to the United Nations Framework Convention on Climate Change (UNFCCC), including the National Determined Contribution (NDC) as part of the international negotiations of the Paris Agreement. (INECC, 2022).

The INEGYCEI is developed using the methodology of the IPCC guidelines and is updated periodically to be presented in Mexico's National Communications to the UNFCCC. The inventory contains the result of the estimation of the emissions and removals of greenhouse gases and compounds deriving from energy, industrial processes and the use of products, agriculture, forestry and other uses of land and waste. The most recent version of the INEGYCEI includes emission estimates of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and BC for the period 1990 to 2019 (INECC, 2021).

3.3. Emission inventory of the Mexico City Metropolitan Area

Parallel to the preparation of the INEM and the INEGCEI, the authorities of the Secretariat of the Environment of Mexico City (SEDEMA, *Secretaria del Medio Ambiente*) and the State of Mexico, in coordination with the DGIELGCA, have established a working group with extensive experience in the development of the emissions inventory of criteria pollutants, GHGs, and short-lived climate forcers (SLCF)[1] from the main emission sources of the metropolitan area of Mexico City (MCMA). In various versions of the inventory, emission estimates from several municipalities in the State of Mexico that are part of the MCMA have been included also to create the MCMA Criteria Pollutant Emissions Inventory (IE-ZMVM, *Inventario de Emisiones Contaminantes de Criterio de la ZMVM*). The IE-ZMVM reports the results with a geographic coverage that includes the 16 boroughs (*alcaldías*) of Mexico City, 59 contiguous municipalities of the State of Mexico and the municipality of Tizayuca, Hidalgo.

Since the early 1990s, SEDEMA has published the IE-ZMVM every two years and covers the four general categories: point sources (industry), area sources (services and residential), mobile sources (transportation), and natural sources (vegetation and soil). The most recent version of the IE-ZMVM is available for the 2018 base year (the 2020 emissions inventory is being prepared and will be published during the second half of 2023), which also includes emissions of toxic pollutants and GHG (expressed as CO_2eq) of the 16 boroughs of Mexico City, 59 contiguous municipalities of the State of Mexico and the municipality of Tizayuca, Hidalgo (SEDEMA, 2021). Table 3.1 summarizes the estimates of polluting emissions during 2018 by type of source and jurisdiction while Figure 3.1 shows the percentage contribution of emissions by pollutant, source and jurisdiction.

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[1] Short-lived Climate forcers (SLCF) are also known as Short-lived Climate pollutants (SLCP).

Table 3.1. Emission inventory of pollutants for the MCMA in 2018 by sources and jurisdiction (SEDEMA, 2021)

Tipo de fuente	**Jurisdicción**	**Emisiones ZMVM, 2018 [t/año]**									
		PM$_{10}$	**PM$_{2.5}$**	**SO$_2$**	**CO**	**NO$_X$**	**COV**	**NH$_3$**	**Tóxicos**	**CO$_2$eq**	**CN**
Fuentes puntuales	**Local**	1,073	754	110	1,971	2,085	14,202	46	5,834	2,691,512	102
	Federal	3,112	2,420	908	3,768	7,421	4,801	94	2,717	11,548,040	432
	Subtotal	**4,184**	**3,174**	**1,019**	**5,739**	**9,506**	**19,003**	**140**	**8,551**	**14,239,552**	**534**
	Aporte	**12.0%**	**19.2%**	**33.2%**	**0.8%**	**6.6%**	**4.6%**	**0.3%**	**7.0%**	**19.0%**	**20.4%**
Fuentes de área	**Local**	15,313	5,837	812	31,520	8,587	257,366	44,218	80,329	16,536,626	538
	Federal	72	69	179	2,378	2,037	13,767	1	3,856	533,269	16
	Subtotal	**15,385**	**5,906**	**991**	**33,898**	**10,624**	**271,133**	**44,219**	**84,185**	**17,069,895**	**555**
	Aporte	**44.2%**	**35.8%**	**32.3%**	**4.6%**	**7.4%**	**65.5%**	**94.2%**	**69.0%**	**22.7%**	**21.2%**
Fuentes móviles	**Local**	10,367	4,361	768	679,781	114,111	90,315	2,539	25,092	42,158,128	1,131
	Federal	3,396	2,737	290	9,473	10,004	1,456	33	399	1,697,932	395
	Subtotal	**13,763**	**7,098**	**1,059**	**689,254**	**124,115**	**91,771**	**2,572**	**25,491**	**43,856,060**	**1,526**
	Aporte	**39.6%**	**43.0%**	**34.5%**	**94.6%**	**85.8%**	**22.2%**	**5.5%**	**20.9%**	**58.3%**	**58.4%**
Fuentes naturales	**Local**	1,447	322	N/A	N/A	353	31,914	N/A	3,778	N/A	0.3
	Federal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Subtotal	**1,447**	**322**	**N/A**	**N/A**	**353**	**31,914**	**N/A**	**3,778**	**N/A**	**0.3**
	Aporte	**4.2%**	**2.0%**	**N/A**	**N/A**	**0.2%**	**7.7%**	**N/A**	**3.1%**	**N/A**	**<0.1%**
Total ZMVM	**Local**	28,200	11,274	1,691	713,272	125,136	393,797	46,804	115,033	61,386,266	1,772
		81.1%	68.3%	55.1%	97.9%	86.5%	95.2%	99.7%	94.3%	81.7%	67.7%
	Federal	6,580	5,226	1,377	15,619	19,462	20,024	127	6,972	13,779,241	844
		18.9%	31.7%	44.9%%	2.1%	13.5%	4.8%	0.3%	5.7%	18.3%	32.3%
	Total	**34,779**	**16,500**	**3,068**	**728,891**	**144,598**	**413,821**	**46,931**	**122,005**	**75,165,507**	**2,615**

Notas: N/A: no aplica, el contaminante no es emitido por la fuente referida. Los totales pueden variar por el redondeo de cifras.

According to the 2018 IE-ZMVM, the transport sector is responsible for 50% of fossil fuel consumption and is the main emitter of PM$_{2.5}$ (43%), PM$_{10}$ (40%), CO (95%), SO$_2$ (35%) and NOx (86%). Within the mobile sources, the main emitter of PM$_{2.5}$ are diesel vehicles, which are mostly heavy units such as buses, tractor-trailers and cargo vehicles due to the low penetration of more efficient technologies (for example, EURO VI or EPA 2010) and emission control equipment (for example., particulate filters). On the other hand, private transport (cars, SUVs, motorcycles) contributes significantly to the rest of the priority pollutants, as these units are the most numerous. Mobile sources also contribute approximately one fifth of the emissions of VOCs and toxic compounds, basically coming from gasoline-powered units.

In the industrial sector, metallurgical and electricity generation industries are the main sources of PM emissions, while paper industry and the manufacture of products based on non-metallic minerals are the main sources of SO$_2$ and also contribute to PM emissions. Point sources contribute to VOC emissions, mainly from printing and related industries, and the chemical industry.

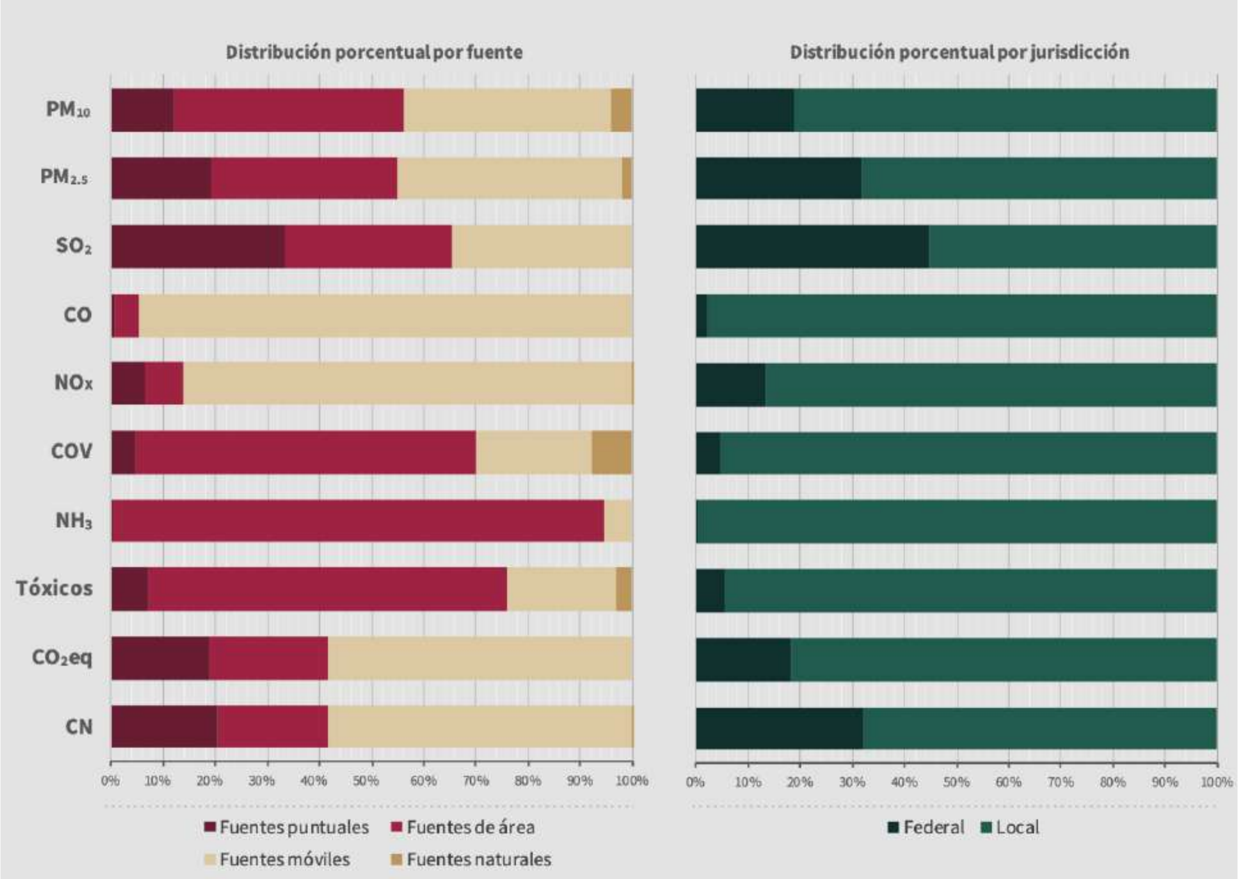

Figure 3.1. Contributions by sources to the total emissions of pollutants in the 2018 MCMA emissions inventory (SEDEMA, 2021)

Area sources, although may not emit very much individually due to their small size, but when added together, account for significant contributions of PM, CO_2, VOCs, NH_3, SO_2 and toxics. As shown in Table 3.1, area sources are the main emitter of VOCs (66%). More than 30% of VOC emissions are due to the commercial and domestic use of solvents in everyday consumer products, such as those for personal care, pesticides, architectural coatings and automotive care products. One fifth of VOC emissions result from leaks at LPG facilities. Another important source is the disposal of solid and liquid urban waste. Area sources such as domestic and commercial use of solvents, untreated wastewater and open air waste burning are important sources of toxic compounds (69%). As part of the strategy to reduce waste generation in CDMX, as of January 1, 2021, the marketing, distribution and delivery of single-use plastic bags and other plastic products were prohibited[2]. The Mexico City government also announced the opening of the hydrothermal

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[2] "Prohibición de plásticos de un solo uso." Disponible en https://gobierno.cdmx.gob.mx/noticias/prohibicion-de-plasticos-de-un-solo-uso/ (Accessed May 16, 2023).

carbonization plant located in Bordo Poniente landfill site, which will convert organic waste into electricity and charcoal pellets with zero GHG emissions[3].

Dust suspension from on-road traffic, agricultural activities and open burning of waste contribute significantly to PM_{10} and $PM_{2.5}$ particle emissions. Area sources are also significant emitters of greenhouse gases and compounds, as noted below. Other activities that are accounted within the area sources include forest fires and structure fires, which are extraordinary and transient events, and when combined with adverse meteorological conditions, can seriously aggravate air quality in the MCMA and other regions of the Megalopolis. As part of the fire management strategy for the forest area of the Megalopolis sponsored by CAMe, the Universidad Autónoma Chapingo (UACH, 2021) has prepared a diagnosis to support the entities of the Megalopolis in updating their fire management programs based on the national program prepared by National Forestry Commission (CONAFOR, *Comisión Nacional Forestal*).

The inventory of greenhouse gases and compounds covers four gases (CO_2, CH_4, N_2O and HFCs), which were estimated using IPCC guidelines (IPCC 2006, 2021) and reported together as CO_2eq. As shown in Table 3.1, the transport sector generates the highest CO_2eq emissions (58%), while the industrial sector (mainly paper industry and electricity generation) contributes 19% of the emissions. The area sources accounted for 23% CO_2eq emissions, the main emitters are sanitary landfills, combustion processes in homes and unregulated industries.

When the emissions of each GHG are analyzed individually, the use of fossil fuels in transport, housing and industry is the main source of CO_2. For CH_4, one of the short-lived climate forcers, most of the emissions are due to the disposal and treatment of solid and liquid waste, along with livestock activities. The emissions of black carbon, another short-lived climate forcer, was also estimated. Transportation is the main emitter of BC, as this is a fraction of $PM_{2.5}$. Heavy-duty diesel vehicles have the largest BC contribution, while other important categories are electricity generation, agricultural and construction machinery, open-air burning of solid waste, and paved roads.

Within the natural sources, vegetation contributes about 7.7% of the total VOC emissions, mainly isoprene and monoterpenes from trees, while wind erosion contributes to PM_{10} (4.2%) and $PM_{2.5}$ (2%) emissions.

As mentioned above, it is important to improve the emission estimates by reducing the associated uncertainties. In the case of the MCMA, the emissions inventory is well developed and seeking its improvement continuously; however, the uncertainties in emission estimates must be further reduced by updating and improving emission factors and activity data, updating the regulations, and standardizing them at the regional and national levels. Among the main challenges to reduce uncertainties in emissions inventories, the need to standardize the emission estimation procedures for Mexico City and the other entities of the Megalopolis stands out. The lack of standardization of procedures also makes it difficult to compare inventories and develop control programs at the

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[3] "Planta de Carbonización Hidrotermal de la Ciudad de México, una revolución tecnológica" Disponible en https://gobierno.cdmx.gob.mx/noticias/planta-de-carbonizacion-hidrotermal-de-la-ciudad-de-mexico-una-revolucion-tecnologica/ (Accessed May 16, 2023).

regional level. Additionally, the fact that there is no continuous inventory evaluation program in the MCMA that is based on field measurements presents a greater challenge to knowing the reliability of the estimates.

SEDEMA has made concerted effort to improve the inventory of VOCs emission as it is one of the major uncertainties in modeling O_3 formation. One of the challenges in reducing the uncertainty in the VOCs emissions is the informal sector. For example, LPG leaks continue to be the main source of VOC, particularly propane and butane, since it was characterized during the MCMA-2003 campaign (Velasco et al., 2007). While LPG is the main fuel used in residential sector, LPG cylinders are also known to be used in the informal sector. Therefore, it is necessary to carry out a diagnosis to determine how much LPG from the domestic sector are actually consumed in the informal sector, as well as estimating what comes from the propellant system of aerosol cans. Additionally, no VOC emissions from the informal food sector have been estimated, for example, fried foods; it is essential to have data on consumption statistics by type of fuel in this sector.

In general, the information compiled in the inventory of SEDEMA and the State of Mexico has been essential for supporting CAMe in the design of policies to improve air quality in the metropolitan area, including the orientation of the programs for the activation of environmental contingencies, and in air quality dissemination and forecasting activities as established in the ProAire.

3.4. Challenges and recommendations to improve the estimation of emissions

- ***Incorporation of quality control methods during the development of emissions inventories***. It is important that the working groups responsible for the development of emissions inventories relevant to the Megalopolis implement the available quality control methodologies during the preparation of emissions inventories. The systematic application of quality control during the development of an inventory is crucial to obtain coherence, integrity, comparability, representativeness, and transparency of the information obtained.

  The application of quality controls allows identifying the main areas of uncertainty in the inventory, as well as the existing challenges to improve the estimates in each successive version. Quality control must be incorporated with statistically robust techniques parallel to the inventory preparation and not after. One of the main challenges to systematically incorporate quality control processes is to institutionalize support to the working groups in terms of allocating the necessary financial, infrastructure, and training resources.

- ***Independent evaluation of inventories*.** The inventories of the INEM, INEGYCEI, and the IE-ZMVM generally use a combination of methods for estimating emissions that include: (1) direct sampling of sources (mainly for industrial sources); (2) indirect estimates using a combination of mass balance techniques and models, for example, MOVES-Mexico, Modelo Mexicano de Biogas, the Non-Road model for off-road sources, and the Emissions and Dispersion Modeling System (EDMS), among others; and (3) extrapolation techniques for the combination of emission factors with activity data; and (4) IPCC guidelines for estimating GHG emissions.

The joint application of the various methods represents a significant effort to obtain, process, and analyze the information necessary to develop the emissions inventories. However, it is necessary to incorporate techniques to assess uncertainty and independent reviews. Estimated emissions inventories must be based on the verification and analysis regardless of the sources of information used. The first challenge to be solved is the systematic promotion of the work and the continuous collaboration with federal, state and local institutions and agencies that generate and process the activity data information to ensure consistency between reported data, the approximations used, and the data obtained under real operating conditions.

The experience of the measurement campaigns in the MCMA in 2002, 2003, and 2006 (Molina et al., 2007; 2010) showed that joint information from field studies, modeling activities, monitoring networks, focused consultations and guided tours, is an important tool that can be used successfully for evaluation and analysis of emissions estimated in local inventories. Some valuable tools for independent emissions assessment use indirect methods such as independent emissions modeling in combination with emission measurement campaigns, as well as long-term studies with the joint application of various techniques, including remote sensing for mobile and industrial sources, inverse modeling techniques, satellite information processing, eddy covariance flux towers for area sources, sampling in tunnels and with portable systems for vehicular emissions, among others.

- ***Updating of emission factors and activity data.*** Due to the continuous changes in technology, fuel regulatory requirements, and changes in the activities that affect the emission processes, periodic updating of emission factors and activity data is necessary. It is essential that decision makers and the environmental authorities of the Megalopolis promote field studies and surveys to update the information used in inventories.

  There are key emission sources that must be prioritized for regular updating of emission factors and activity data, examples of these sources include: gasoline vehicles, off-road vehicles, motorcycles, heavy-duty diesel vehicles and those used in the transportation of passengers and cargo. Emissions from resuspension of dust on roads, VOCs emissions from paints, the handling of solvents, disinfectants, cleaners, waterproofing, and infectious waste, as well as emissions from cooking in the informal and service sectors, are examples of key sources with high uncertainty in their estimates and which must be continually reviewed.

- ***Coordination between environmental authorities and working groups that develop emission inventories.*** It has been observed that each entity that makes up the Megalopolis is both an emitter and a receiver of pollutants, so it is necessary to strengthen coordination between the different entities to improve emission estimates at the regional level. In addition, it is essential to improve coordination between the working groups that prepare emissions inventories, which will allow the generation, processing and analysis of information to be efficient and transparent. This will contribute to improving air quality management and reducing pollution levels in the Megalopolis. It is important to understand the regional emission and transport of pollutants to coordinate control measures within the Megalopolis. Many public policies will only be able to maximize their benefit if there is coordination between the government agencies of the different entities.

- ***Increase and expand technical capabilities***. As part of the implementation of a process to improve coordination between environmental authorities, it is also important to increase and expand the technical capabilities for the preparation of inventories by the working groups of the different entities of the Megalopolis at the federal, state, and municipal levels. Better coordination and increased technical capacities of the working groups are necessary steps to generate (in successive versions) a regional emissions inventory for the Megalopolis that is comprehensive, robust, accurate, reliable and that serves as support in modeling, forecasting, and design of programs that improve air quality. It is necessary that the reports of the emissions inventories, the calculation methodology and the management of uncertainties be publicly accessible.

- ***Improve the estimation of mobile sources*.** In the case of vehicle emissions, currently most of the inventories in Mexico are developed using the MOVES-Mexico model, which is an adaptation of the MOVES (Motor Vehicle Emissions Simulator) model of the United States Environmental Protection Agency (US EPA). The MOVES-Mexico model allows estimating emissions by adjusting the calculations with local databases, such as data from monitoring campaigns with remote sensors, data from vehicle verification programs, emissions tests on new vehicles and fuel formulation, in addition to the meteorological conditions and local and regional characteristics. However, a major challenge in adjusting the estimate of mobile source emissions using the MOVES-Mexico model is the adequate representation of real driving conditions. Therefore, due to the particularities of traffic that different cities have, the estimates of the emission factors and activity data must be improved.

  The first version of MOVES-Mexico was used in the country in 2016, making adjustment to the United States MOVES model version 2014a, for the estimation of on-road vehicles emissions. In 2022, the model for Mexico was updated as MOVES-Mexico 2022, adjusting the databases with recent information from remote sensing, vehicle verification programs, vehicle fleet and activity. The model will be publicly available during the second half of 2023.

  The MOVES-Mexico 2022 version was based on the 2014b version of the United States MOVES, instead of MOVES3 (US EPA, 2022), which was published by EPA in 2022 and included the state of the science on emissions from mobile sources. However, the MOVES3 modifications would not apply in Mexico, since they present new emissions measurements in the United States and also adjustments to the emissions of off-road vehicles whose emission factors have not been evaluated for Mexico.

  As part of the SLCF campaign coordinated by the MCE2 in Mexico City in 2013, the components of PM (BC, organic carbon and other inorganic components of $PM_{2.5}$) and gases (CO, NO_X, SO_2, VOC) present in the emissions of various diesel vehicles (buses, cargo trucks) with different model years and emission control technologies were determined under real driving conditions using the chasing technique with the Aerodyne Mobile Laboratory (see Chapter 4, Section 4.5). Comparison of the results with the US-EPA MOVES 2014b model showed disagreements for several species, demonstrating the need to use a database with locally obtained emission factors to reduce uncertainty in emission estimates (Zavala et al., 2017a). It is necessary to consider not only adjusting the MOVES-Mexico model to local conditions, but also updating its base version to improve the estimates.

In 2014, emission factors for gases (CO, CO_2 and NO_X) and PM (the BC component and total PM) were also obtained for a variety of off-road diesel vehicles (construction and agricultural equipment) with and without diesel particulate filters, using the Portable Emission Measurement Systems (PEMS) technique at high temporal resolution. Results showed that the reductions for BC emission factors were significantly higher (> 99%) with filters installed (Zavala et al., 2017b). Unlike on-road vehicles, there is no regulation for the emission levels of off-road vehicles, but the development of a standard (NOM) is in the process. Their relative contributions increase over time as road vehicle emissions continue to be reduced through the use of better technologies. There is a great need to increase the database of emission factors for off-road vehicles through field studies and to continue studying the benefits of emission control technologies for these vehicles in the Megalopolis.

In addition to emissions from automobile exhaust systems, it is important to characterize evaporative emissions from the fuel system and those from wear and tear or tires, brakes, and other non-exhaust systems, which include toxic metals.

The project "Emissions inventory of pollutants from on-road mobile sources for the Megalopolis with base year 2018 and the update of the MOVES Mexico model" (*Inventario de emisiones contaminantes de fuentes móviles carreteras para la Megalópolis con año base 2018 y la actualización del modelo MOVES México)* by CAMe and SEMARNAT, financed with resources from FIDAM-1490, is currently being executed. This project will support and provide training to the seven entities that make up the CAMe for the development and updating of their emissions inventory.

- ***Improve the estimation of evaporative emissions from fossil fuels***. It is currently known that the evaporation of gasoline during transfer operations is an important source of emissions of organic compounds in the Megalopolis. Fuel evaporation also represents energy inefficiency and a significant economic loss. Furthermore, it has negative impacts on the health of the population due to the high toxicity of several of its organic compounds and its decisive participation in the formation of O_3 and secondary organic aerosols. It is therefore necessary to control evaporation losses during the fuel handling and supply processes at gas stations and service stations.

  The control of fuel losses due to evaporation during the transfer and supply processes must be based on a comprehensive strategy of regulation, optimization, updating and improvement in the different phases of the distribution, from refineries, storage terminals and service stations, as well as in the application of technical methods to measure emissions and evaluate their efficiency. It is necessary to guarantee the reduction of emissions during storage, transfer and sale through the Vapor Recovery Systems (VRS), whose operation must be continuous and efficient in accordance with NOM-004-ASEA-2017.[4] The NOM-006-ASEA-2017[5] establishes the specifications, technical criteria and requirements for industrial safety, operational safety and environmental protection that must be carried out in on-shore storage facilities for petroleum and petroleum products. The standard indicates that the facilities must control gasoline vapors during the loading of tanker trucks with an efficiency equal to or greater than 95%, but it does not establish the test methods, so there is currently no evidence of its operation and quantification of emission control. Similarly, NOM-005-ASEA-2016[6] indicates that service stations must have hermetic devices to control gasoline vapors during the unloading of tanker trucks. However, the standard does not establish the parameters or test methods. Currently, through a CAMe project, the coverage and performance of VRSs at gas stations is evaluated and modifications to NOM-005-ASEA-2016 and NOM-006-ASEA-2017 will be proposed.

- ***Improve estimates of industrial sources.*** The estimates mainly apply the US EPA emission factors, which are not necessarily applicable to the operating and technological conditions of industrial processes in Mexico. Furthermore, when rigorous quality control is not followed, the calculations tend to have errors and the vast majority of the data recorded in the Annual Operation Certificates (COA, *Cédulas de Operación Anual*) do not have the necessary operational representativeness for emissions inventories. The data are recalculated considering activity data, historical information and other information sources, because the industry reports have multiple errors. Several entities do not have the annual reports from the industry under state jurisdiction or they do not report annually or reliably. There is also large uncertainty regarding fugitive emissions and the operating efficiency of control systems reported by the industry. These limitations underscore the need to reduce uncertainty in the estimates from industrial sources.

- ***Improve estimates of area sources.*** Area sources are small but numerous and contribute significantly to PM, CO_2, VOCs, NH_3, SO_2, and toxic compounds emitted from diverse

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[4] Diario Oficila de la Federación, Norma Oficial Mexicana NOM-004-ASEA-2017, Sistemas de recuperación de vapores de gasolinas para el control de emisiones en estaciones de servicio para expendio al público de gasolinas-Métodos de prueba para determinar la eficiencia, mantenimiento y los parámetros para la operación. https://www.dof.gob.mx/nota_detalle.php?codigo=5513203&fecha=14/02/2018#gsc.tab=0.

[5] Diario Oficial de la Federación, Norma Oficial Mexicana NOM-006-ASEA-2017, Especificaciones y criterios técnicos de seguridad industrial, seguridad operativa y protección al medio ambiente para el diseño, construcción, pre-arranque, operación, mantenimiento, cierre y desmantelamiento de las instalaciones terrestres de almacenamiento de petrolíferos y petróleo, excepto para gas licuado de petróleo. https://www.dof.gob.mx/nota_detalle.php?codigo=5533266&fecha=27/07/2018#gsc.tab=0.

[6] Diario Oficial de la Federación, Norma Oficial Mexicana NOM-005-ASEA-2016, Diseño, construcción, operación y mantenimiento de Estaciones de Servicio para almacenamiento y expendio de diésel y gasolinas. https://www.dof.gob.mx/nota_detalle.php?codigo=5459927&fecha=07/11/2016#gsc.tab=0.

sources including: product storage and transport distribution (gasoline, LPG), commercial and domestic use of solvents, consumer products, waste management (landfills, open trash burning, wastewater treatment, sewage), agricultural activities (crop burning, tillage, application of fertilizers and pesticides, cattle feedlots, enteric fermentation, manure management), dust resuspension, among others. In contrast to large stationary sources, area sources are generally required to meet less stringent emissions limits. Many of the micro industries belong to the informal industry sector which are not effectively regulated; they are too small to be inventoried, contributing to one of largest uncertainties in emission estimates. For example, area sources contributed to 66% of VOCs in the MCMA in 2018 (SEDEMA, 2021). There are numerous small manufacturing, painting, mechanical service workshops, among others, that are part of the informal sector that together can have significant contributions of some pollutants such as VOCs. As the urban VOCs emissions from transportation-related sources have decreased due to technological advances and regulatory measures, volatile chemical products from sources such as personal care and household products, aerosol coating, painting, solvent use and pesticides have gained in importance, highlighting the need for regulatory actions to control the sources. As described below under specific categories (VOCs, biomass burning, greenhouse gases), it is important to support field measurements to estimate the emission factors for area sources, as well as studies to improve the estimate of activity data.

- ***Characterization of emissions of VOCs and toxic organic compounds.*** Volatile organic compounds (VOCs) are of interest in part because they participate in atmospheric photochemical reactions that contribute to ozone formation and they play a role in the formation of secondary organic aerosols. Additionally, many individual VOCs are known to be harmful to human health (air toxics).

  The inventory of VOCs emission is one of the largest uncertainties in emissions estimates. VOCs in the MCMA during 2018 are emitted from a variety of sources, including motor vehicles, chemical manufacturing facilities, refineries, factories, consumer and commercial products, and natural (biogenic) sources (mainly isoprene and monoterpenes from trees). Around two thirds of the total emissions (66%) are generated by area sources, including the commercial and domestic use of solvents, along with LPG leaks (mainly propane and butane) (SEDEMA, 2021)..

  The commercial and domestic use of solvents contributes about 32% of the total VOC emissions. Within this activity, certain products have a greater contribution, such as personal care products, pesticides and other products for domestic consumption, industrial cleaners, architectural coatings and automotive care products. With this in mind, the creation of standards that limit the VOC content in priority products should be encouraged, while at the same time promoting the acquisition of merchandise with lower content of these substances. Efforts to control VOC emissions should also focus on addressing LPG leaks in homes, businesses, services and industries, which together generate 20% of emissions. Measures are required to reduce leaks, promote responsible consumption of this energy, and move towards more environmentally friendly fuels and renewable-energy technologies, such as solar heating system and solar water heaters.

Toxic pollutants are compounds that have the capacity to directly produce adverse effects on the health of the population or the environment. Most of these pollutants are VOCs such as toluene and xylenes, although the classification also includes elements such as lead, other heavy metals, phosphorous, and their compounds.

Toxic organic compounds represent 29% of total VOC emissions and area sources are the main source of emission, with a contribution of 69% of total toxics in the MCMA in 2018. The main emitting activities are related to the domestic and commercial use of solvents, urban waste management, and the distribution of gasoline (SEDEMA, 2021).

Efforts are currently underway to improve the characterization of unregulated toxic organic compounds in the Megalopolis. An example is the use of aerosol thermal desorber techniques - gas chromatograph - mass spectrometer (TAG-GC-MS) by the Atmospheric Sciences group at ICAyCC-UNAM (Amador-Muñoz et al., 2022). The objective of these activities is to improve the understanding of the origin of compounds such as polycyclic aromatic hydrocarbons (PAH) and their relationship with mobile and industrial sources, solvents, household products, paints, waterproofing, garbage and personal use products, among others.

Due to its relevance in atmospheric chemistry and its toxic effects, it is important to maintain and increase support for studies aimed at the characterization of emissions of VOCs and toxic organic compounds. In addition to characterizing the chemical speciation of VOCs, studies should prioritize a better understanding of the spatial and temporal distributions of organic compounds in the Megalopolis.

- ***Emissions from motorcycles***. An important challenge is the regulation of the use of motorcycles and the improvement of the estimation of their emissions in the Megalopolis. In recent years, the growth in motorcycles use in the region has been explosive. Among other factors, the growth is due to the versatility of this type of units to circulate under conditions of high traffic congestion (generally ignoring traffic regulations), the lower acquisition price, and the lack of adequate regulation. The importance of regulating the use and maintenance of motorcycles, as well as improving the estimates of their emissions, lies in the fact that most of them circulate with highly polluting emitting technologies and can potentially negatively impact air quality. Currently there are no regulations for motorcycle emissions, but SEMARNAT is coordinating a working group for the preparation of a NOM project to limit its emissions.

- ***Improve estimates of fires, biomass burning and dust storms***. Biomass burning is one of the largest sources of trace gases and aerosols emitted to the global atmosphere and is the dominant source for black carbon and primary organic aerosols (Andreae, 2019). Fire smoke is also a major source of greenhouse gases, including CO_2, CH_4, and N_2O. Other emitted pollutants include CO, volatile, semi-volatile, and nonvolatile organic compounds, NO_x, NH_3, hydrogen cyanide (HCN) and nitrous acid (HONO). There are many sources and types of fires related to biomass burning emissions; some are natural sources such as uncontrolled and unplanned wildfires, while others, such as emissions from burning of crop residue, municipal solid waste, residential wood burning for cooking and heating, and biofuel for brick production, are the results of human activities. Different approaches had been used to estimate emission factors for biomass burning in Mexico City and surrounding region, including direct measurements over fires in field experiments (Christian et al., 2010; Zavala et al., 2018), aircraft measurements (Yokelson et al, 2007, 2011) and laboratory measurements (for example, Zuhelen et al., 2021, Santiago de la Rosa, 2018). In spite of significant progress in emission factor measurements, detection and quantification of biomass burning, there is still a need to improve the accuracy in the activity estimates, both for open burning and biofuel use.

The evidence suggests that the exceptional episodes of high level of pollutants in the region are linked to particular meteorological conditions, together with the contribution of large regional emission sources, such as the burning of biomass (agricultural and forestry) and the emissions of particulate matter from exposed and eroded soil. It is important to promote and support field, monitoring, satellite, and modeling studies to better characterize emissions from these sources and thus manage the procedures to be followed by the population and environmental authorities during environmental contingencies.

- ***Improve estimates of greenhouse gases.*** The IPCC guidelines are generally used to estimate greenhouse gas emissions with comparable techniques in all countries, including Mexico. As part of the SLCF campaign, coordinated by MCE2, to characterize the main sources of BC, CH_4, and associated pollutants, field studies carried out in Mexico to characterize CH_4 emissions from wastewater treatment plants and livestock enteric fermentation indicated that the IPCC methodologies are an inaccurate tool for estimating local GHGs (see Chapter 4, Section 4.5). It is important to determine specific emission factors for each emitting source to more accurately estimate GHG emission inventories. Based on these best estimates, more effective mitigation policies can be identified and applied.

  In addition, field studies demonstrated the importance of obtaining emission factors for BC and associated pollutants, under real operating conditions from on- and off-road vehicles, brick kilns, and stoves, to improve emission estimates, since Mexico was the first country committed to reducing BC as part of its NDC submitted to the UNFCCC.

- ***Incorporation of satellite data for the evaluation of emissions.*** There are efforts by the academic sector in conjunction with environmental authorities to incorporate the use of satellite information as a tool for evaluating emissions inventories. An example is the use of NO_2 and formaldehyde (HCHO) columns from the TROPOMI instrument of Sentinel-5P to assess changes in emissions in regions of the Megalopolis. Due to their large potential for evaluating emission estimates in inventories, it is important that the use of these techniques be expanded in Mexico. The incorporation of satellite data for the evaluation of emissions should also include the application of techniques that characterize the vertical structure, mixing, ventilation, and dispersion processes of the atmosphere such as ceilometer measurements, radiosondes, Doppler lidars and modeling exercises (for example, Burgos-Cuevas et al., 2021; García-Franco et al., 2018). The integration of these techniques is necessary to understand and predict the interaction between emissions, meteorology, and pollution levels in the Megalopolis.

CHAPTER 4. ATMOSPHERIC SCIENTIFIC RESEARCH IN THE MEGALOPOLIS

4.1. Atmospheric processes

The study of atmospheric processes constitutes a fundamental activity to understand the impacts and evaluate the best options for mitigating air pollution. The Mexico City Metropolitan Area (MCMA) has an abundant history on the study of the physical and chemical processes that control the emission, transformation, and transport of atmospheric pollutants, including ozone (O_3) and particulate matter (PM) (Molina et al., 2007, 2010, 2019). A review of available atmospheric science studies in the MCMA and other entities of the Megalopolis indicates that the commonly used tools for this purpose include:

1) Design and implementation of environmental monitoring networks, mainly in urban areas.
2) Continuous and systematic development of inventories of emissions from sources at local and regional scales.
3) Field measurement studies of atmospheric pollutants.
4) Characterization of various sources of emissions.
5) Meteorological modeling studies and the transport, transformation, and fate of pollutants in the atmosphere.
6) Air quality modeling and forecasting.
7) Impacts of air pollutants on public health.
8) Cost-benefit studies of air pollution control.

There are also public reports and applications on social networks that are issued periodically to report on air quality conditions in the MCMA and in other cities of the Megalopolis. The continuous disclosure of information is intended to help the population make decisions that reduce exposure to air pollutants. Furthermore, some of the most important results of the development of these tools were incorporated into the public agenda through environmental regulations and legislation, as well as in the design of state, regional and national plans to control atmospheric pollution, including actions to be carried out during environmental contingencies. At the same time, some efforts are underway to develop financial and institutional capacities, infrastructure, and strengthening human resources that allow the implementation and compliance of air pollution control plans.

The actions described above have contributed to the improvement of air quality in the MCMA for some pollutants, especially when compared to the levels of pollution to which the population was exposed in the decades of 1990-2000. However, current observations clearly indicate that key pollutants have not decreased to acceptable levels. Furthermore, the atmospheric concentrations of pollutants such as O_3 and PM have begun to increase in recent years (Velasco & Retama, 2017; Zavala et al., 2020). This suggests that it is a priority to update scientific knowledge on the processes that control the formation, transport, and fate of these pollutants (Molina et al., 2019; Velasco et al., 2021; Molina, 2021). This interest is reflected in the MCMA ProAire 2021-2030 to recapture the trend of reducing air pollution and its impacts on health and improving the quality of life of the population (SEDEMA et al., 2021).

4.2. Scientific challenges of characterization of atmospheric pollutants

This section describes the main aspects that limit the current knowledge of atmospheric pollutants, with special emphasis on the formation, transport, and fate of O_3 and PM.

4.2.1. Characterization of ozone in the Megalopolis

4.2.1.1. Ozone formation and destruction processes

Ozone formation in urban areas is a complex process that is determined by the local relative abundance of volatile organic compounds (VOCs), and nitric oxide (NO) and nitrogen dioxide (NO_2), as well as the available solar radiation. O_3 is produced from the photolysis of NO_2 and the subsequent reaction with atmospheric O_2, therefore the amount of NO_2 available is key in the process. NO_2 can be formed again from the reaction between O_2 and NO, consuming an O_3 molecule. However, the oxidation of VOCs present in the atmosphere offers an effective alternative route for producing NO_2 that bypasses consumption of O_3, as shown in Figure 4.1, which allows greater production and subsequent accumulation of the pollutant.

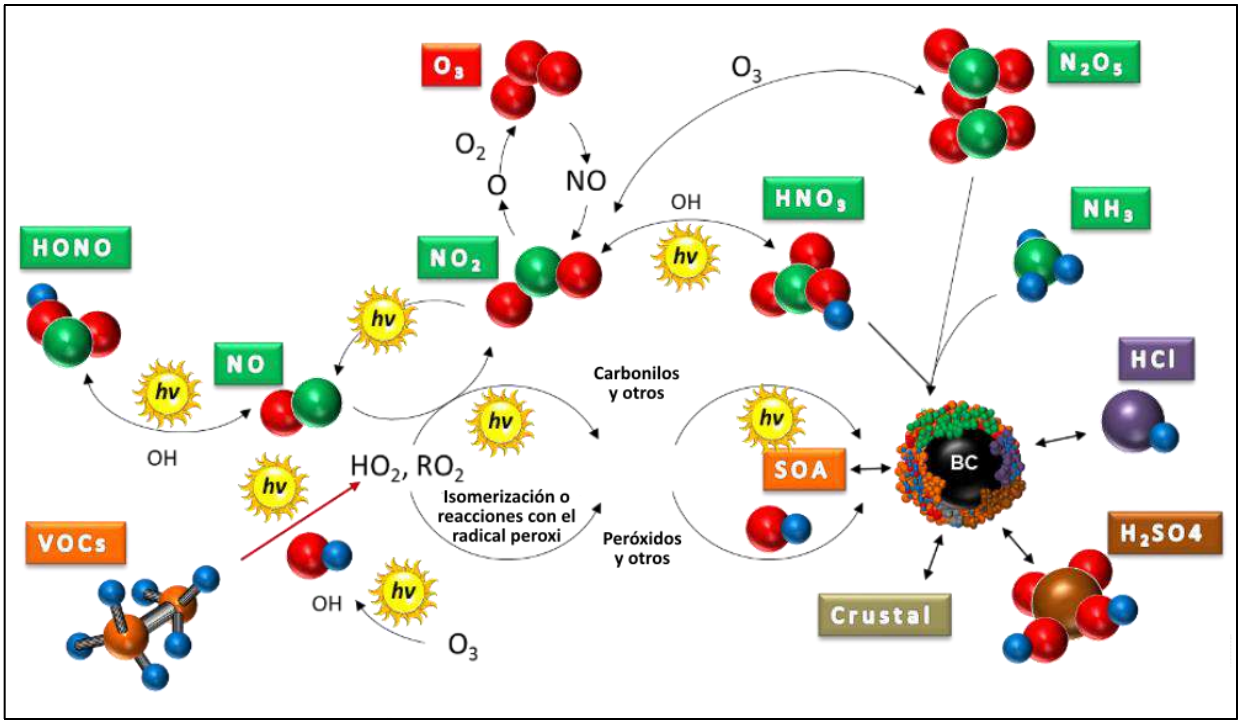

Figure 4.1. The complex formation and destruction of ozone, and formation of secondary aerosols (SOA) and transformation of particles directly emitted to the atmosphere. (Own elaboration).

The formation of O_3 is non-linear because there is a competition for the main oxidant, the hydroxyl radical (OH), between the VOCs and the nitrogen oxides ($NO_X = NO + NO_2$), but while the VOCs are consumed during the formation of O_3, the NO_X are regenerated acting as catalysts. The formation of O_3 is promoted by solar radiation, when it decreases or when any of the precursors decreases, the termination reactions predominate, forming nitric acid (HNO_3), secondary aerosols, hydrogen peroxide (H_2O_2) and peroxyacetyl nitrate (PAN), among other secondary pollutant species. The processes of formation and termination occur continuously in the atmosphere and interact with the meteorological conditions, determining the possible accumulation of O_3 to which the population is exposed.

4.2.1.2. Limitations for the characterization of ozone

Although the previous description of the local formation and destruction of O_3 has been established by the scientific community for several decades, in the Megalopolis and in many other cities in Mexico there are still high levels of O_3 and the activation of environmental contingencies keep happening every year. Given that the processes of O_3 formation and destruction are known, the question is pertinent: What are the barriers that limit our ability to control O_3 in the Megalopolis and other cities?

In principle, the previous description of the chemical processes involved indicates that the main challenges to characterize the local formation of O_3 include: (1) the characterization of the chemical mixtures of VOCs, NO, and NO_2; (2) the determination of the levels of radicals OH, HO_2, and organic peroxides (RO_2); and (3) the abundance of solar radiation. It is also necessary to characterize the background levels of O_3 and of the precursor species. However, in practice it can be very difficult to obtain, integrate, and analyze the required information, coupled with the lack of important data for the characterization of O_3.

The following described some limitations in the knowledge of the physical and chemical processes that control O_3 in the Megalopolis:

1) *Spatial and temporal characterization of VOCs.* As a result of the intensity, heterogeneity, and number of emission sources, VOCs in urban areas are complex mixtures of hundreds or even thousands of organic compounds with a wide range of concentrations, reactivity levels (with OH and other oxidants), and lifetimes. This makes it difficult to properly characterize the spatial and temporal distributions of these compounds, particularly for those that are more reactive and therefore have a high O_3-forming potential (OFP).

2) *Spatial and temporal characterization of radical compounds*. The radical compounds OH, HO_2, and RO_2 are produced through chemical and photolytic reactions involving O_3, HONO, and various carbonyl compounds among other VOCs. However, there are significant technical difficulties in accurately measuring the levels of radical compounds. This occurs because these compounds are highly reactive chemically, which is why their atmospheric concentrations are low and their lifetime extremely short. Although there are currently measurement methods that allow their characterization with sufficient precision, as for the mixtures of radical precursor VOCs, it is still difficult to adequately characterize their spatial and temporal distributions in such a way that they allow their relative

contributions to O_3 formation of for the different areas of the city to be quantitatively evaluated.

3) *Spatial and temporal characterization of NOx*. The measurement of NO and NO_2 presents fewer difficulties than VOCs and radical compounds for their spatial and temporal characterization. However, nitrogenous compounds also participate in various chemical reactions with VOCs and other radicals, which in turn form nitrate radicals (NO_3) and other organic nitrogenous compounds, thereby affecting O_3 destruction rates. Therefore, for the information to be useful in the characterization of O_3, NO and NO_2 compounds must be measured simultaneously and at the same location as VOCs and radical compounds. Not having simultaneous information on the precursors limits the ability to understand the pathways of O_3 formation and destruction.

4) *Limited formation of O_3 in areas close to the emissions of its precursor gases*. The oxidation of VOCs occurs during transformations in the atmosphere; however, the processes of combustion, evaporation or sublimation could emit some species with some degree of oxidation. This characteristic makes it difficult to characterize O_3 in areas with multiple VOCs and NOx emitting sources, as typically occurs in large cities.

5) *Need to characterize background concentrations.* Both the processes of formation and destruction of O_3 occur simultaneously and continuously in air masses that are transported within the urban area. This implies that each air mass includes an initial concentration of O_3 and its precursors that corresponds to background levels. Because the contribution varies spatially according to the history of the downwind and upwind air mass, characterizing that contribution is not straightforward and requires the use of properly evaluated numerical models.

6) *Spatial and temporal variability of meteorological parameters*. Meteorological conditions that modify the intensity of solar radiation in turn affect the formation of O_3. This includes cloudiness, albedo, relative humidity, and even aerosol microphysics of cloud formation. Due to the complex topography in Megalopolis and in other large cities in Mexico, meteorological conditions vary substantially in different regions of the urban areas. Thus, the spatial and temporal dependence on meteorological conditions induces an additional challenge for the characterization of O_3.

7) *Spatial and temporal variability of the mixed layer and local turbulence*. Ambient concentrations largely depend on the state of the mixed layer and production of local thermal turbulence. In addition, due to the phenomenon of intrusion of air masses at different vertical (height) positions, it is essential to know the dynamics of the mixed layer to characterize the O_3.

8) *Local effects*. At the local scale, there are also impacts on wind patterns and available solar radiation induced by the urban canyon effect and the energy exchange with the surfaces. This indicates that the characterization of O_3 must also be carried out with the highest possible spatial resolution within the study area. Conversely, this also suggests that for O_3 control actions to be effective, the characterization must be carried out in multiple zones

such that they comprehensively reflect the formation and destruction processes of the pollutant.

4.2.2. Characterization of particulate matter in the Megalopolis

Numerous studies have highlighted the marked impact of atmospheric particulate matter (PM) on human health, climate, and ecosystems. Particulate matter is solid and/or liquid particles suspended in air, excluding droplets (or crystals) from clouds and rain. Being suspended in air masses, particles can be carried by wind over long distances. Atmospheric particles are emitted directly from natural sources (such as oceans, volcanoes, desert areas) and anthropogenic sources (such as vehicular traffic, industrial activity, biomass burning.) with a wide range of physical properties (for example, size, density, morphology) and chemical composition. The particle fractions used within environmental management are PM_{10} (coarse particles with an aerodynamic diameter of 10 µm or less), $PM_{2.5}$ (fine particles with an aerodynamic diameter of 2.5 µm or less), and ultrafine particles (with an aerodynamic diameter of 100 nm or less).

The characteristics described above emphasize the complexity of understanding the formation, transformation, and fate of particles in Megalopolis and other cities in Mexico. Some of the particles in the atmosphere comes directly from multiple emission sources mentioned above (primary PM). However, nowadays in Mexico City, as in many other cities in the world, most of the atmospheric particles have a secondary origin. Hence this section primarily addresses the contribution to particles derived from reactions between polluting gaseous that act as precursor species in the formation of aerosols in the atmosphere (secondary PM).

4.2.2.1. Formation and destruction processes of particulate matter

Like the formation of O_3, the formation of new particles in the atmosphere is a complex process that begins at the molecular scale and has only recently begun to be understood. Secondary aerosol formation mechanisms are the result of the conversion of atmospheric gases into particles under specific thermodynamic conditions. The formation pathways of inorganic secondary particles in the atmosphere by gaseous precursors such as sulfur dioxide (SO_2), nitrogen oxides (NO_X) and ammonia (NH_3), have been studied for several decades (Seinfeld & Pandis, 2016). But it has been observed that precursor gases can also interact with organic compounds from both anthropogenic sources of combustion and evaporation, as well as from metabolic processes of plants. Previously it was thought that the formation of particles required sulfuric acid (H_2SO_4), which is formed from the oxidation of SO_2, it is now known that certain organic vapors also form particles. In fact, organic particles can form more efficiently when H_2SO_4, ammonia (NH_3), and organic vapors are simultaneously present (Lehtipalo, et al., 2018; Liu et al., 2015; Hao et al., 2020).

The VOCs are oxidized in the presence of the OH radical, but they are also rapidly oxidized by other species such as O_3 and the NO_3 radical. Oxidation can occur in a matter of minutes to hours. The oxidation routes depend on several factors: the abundance of the oxidants, the size and functionality of organic molecules, the water content in aerosols and their acidity, ambient temperature, availability and intensity of solar radiation, among other factors. Reactions with OH and O_3 predominate during daytime, while the NO_3 radical plays an important role at night. Figure 4.2 shows some examples of the formation of new particles from VOCs, which are known as organic aerosols.

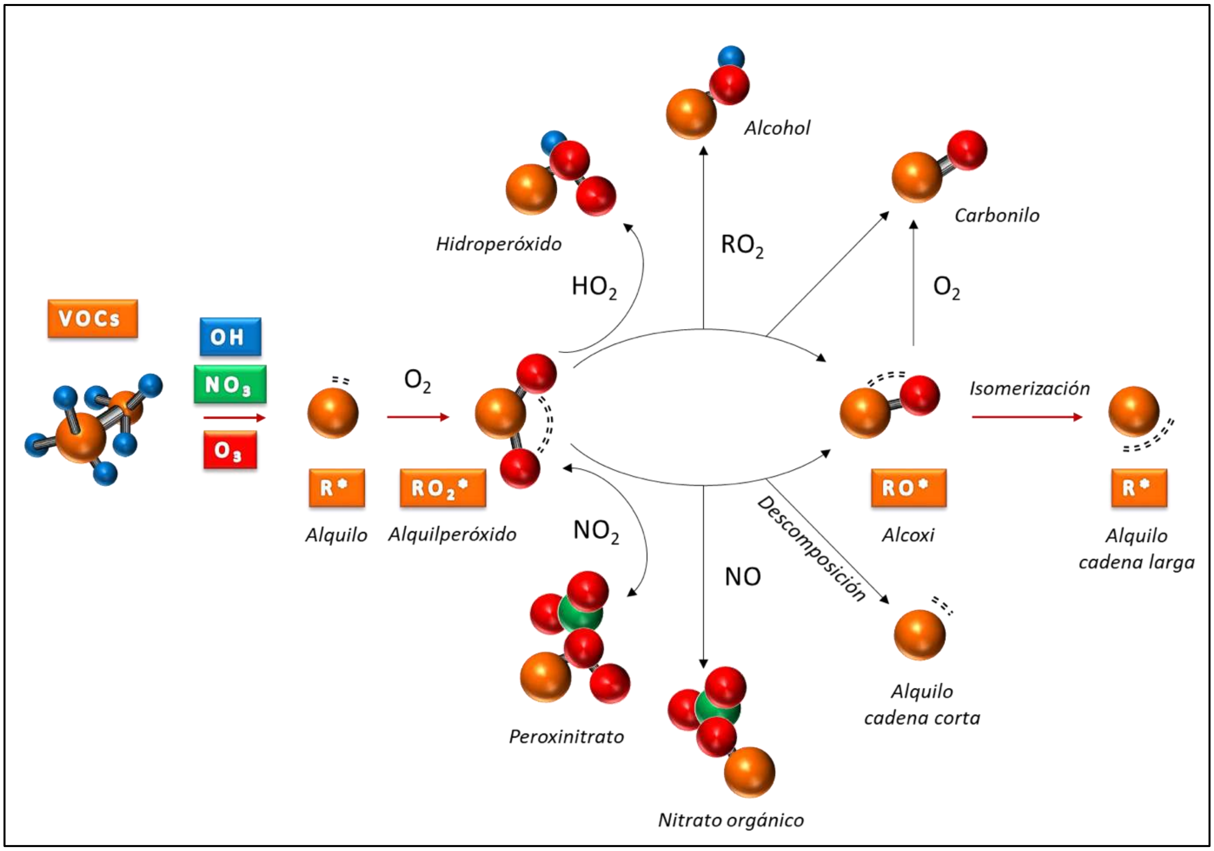

Figure 4.2. Oxidation of VOCs and formation of secondary organic aerosols. (Source: Adapted from Seinfeld & Pandis, 2016).

As shown in Figure 4.2, it is important to know the abundance and variety of VOCs, the levels of NO_X and atmospheric oxidants. Secondary aerosol formation processes can be more complex than those involved in O_3 formation due to the large variety and structural complexity of organic compounds that can be found in the atmosphere, especially in urban environments.

4.2.2.2. Limitations in the characterization of particulate matter

The above description of the formation and destruction of secondary PM shows the complex non-linear relationships that exist between their precursors and the prevailing meteorological conditions. Furthermore, the changing physical and chemical properties of the aerosols due to oxidation mechanisms make it difficult to understand all the processes involved. Current knowledge indicates that the formation of secondary pollutants is closely linked to the components of both aerosol phases: gaseous and particulate. The connection between the chemical and physical processes in both phases occurs through (1) the participation of free radicals present in the atmosphere; (2) the emitting sources of VOCs, NO_X, NH_3, and SO_2, among other precursor gases, and their mixtures; and (3) the transport of air masses and their participation in thermodynamic changes.

As in the case of O_3, in practice it is difficult to compile and analyze the information required for the characterization of secondary aerosols. Some of the main barriers that limit our understanding of the physical and chemical processes that control secondary aerosol formation in the Megalopolis are described below.

1) *Interactions between organic compounds and other precursor gases*. It is important to understand the secondary formation of aerosols through the interaction between organic compounds and other precursor gases. A current question is the impact that the formation of secondary particles would have by reducing the emission of precursor gases. The biogenic emission of volatile organic compounds cannot be controlled in principle, but it is possible to control the emission of precursor gases of anthropogenic origin. Knowing the impact that such reductions would have would help in designing control measures for particulate pollution..

2) *Oxidation processes and formation of condensation nuclei*. Aerosols can affect climate by scattering and/or absorbing solar radiation, and also acting as condensation nuclei in the formation of cloud droplets. The newly formed particles increase in size as they incorporate organic matter during the oxidation processes, until they reach a size where they can act as condensation nuclei in clouds. Oxidation processes occur during the transport of aerosols. Thus, in addition to absorbing and reflecting solar radiation, and thereby contributing to climate change and modifying the energy balance, atmospheric particles can also alter precipitation cycles by altering cloud formation. However, the magnitude of their impacts depending on the type of cloudiness (for example, shallow clouds or cumulonimbus clouds) is not yet clear, which is reflected in the uncertainties presented by current climate models.

3) *Need to increase the spatial and temporal resolution of information on the abundance and chemical composition of precursor gases.* The heterogeneity in the emission sources in urban areas makes it necessary to know the abundance and composition of precursor gases with a certain spatial resolution that allows determining spatial variations in the formation of secondary aerosols. Likewise, it is necessary to know its variability during the year to evaluate changes in the heterogeneous chemistry according to the climatological seasons.

4) *Contribution of emission sources of precursor compounds.* It is necessary to know the relative contribution of different emission sources, both natural and anthropogenic, in the composition of the main chemical species that act as precursor compounds. These include ions, metals, organic carbon, elemental carbon, total carbon, and inorganic components such as sulfate (SO_4^{2-}) and nitrate. (NO_3^-). A comprehensive chemical characterization will allow a detailed evaluation of the performance of the chemical mechanisms used in numerical models to reproduce the formation of secondary aerosols.

5) *Spatial and temporal characterization of radical compounds*. As in the case of O_3, the characterization of radicals (mainly OH and NO_3), which act simultaneously as precursor compounds and oxidative catalysts, is essential to improve our knowledge of the formation of secondary aerosols.

6) *Aerosol oxidation mechanisms*. Oxidation processes, both in the gas phase and in the particulate phase, occur permanently in the atmosphere. The intensity depends on meteorological conditions and levels of chemical reactivity of the mixture of pollutants. Once in the particle phase, semi-volatile compounds in the particles undergo reactions that

decrease their volatility to form compounds of higher molecular weight because the vapor pressure of organic compounds decreases as the number of added atoms increases. An example of this type of reaction is oligomerization catalyzed by H^+ protons (that is, in an acid medium) and contributes to the formation of secondary aerosols. Thus, it is necessary to improve our knowledge of oxidation mechanisms and the effects of acidity on particle formation.

7) *Complexity in the chemical changes in the properties of aerosols*. The oxidation processes induce not only changes in the volatility of the compounds already formed, but also in the concentration, chemical composition, and physical properties of the aerosols. Each oxidative stage or process has the potential to contribute to the formation of secondary aerosols if the necessary conditions are met. Oxidative processes terminate when all organic carbon is completely degraded to CO and CO_2. Therefore, it is necessary to know the changes in volatility during particle formation and their effects on physical and chemical properties.

8) *Concurrent factors to understand ozone formation*. Many of the barriers that hinder understanding of O_3 formation and destruction processes also apply to secondary aerosols. These include: (1) the spatial and temporal variability of meteorological parameters; (2) the spatial and temporal variability of the mixed layer and local turbulence; (3) background concentrations of precursor pollutants; and (4) the local effects on the wind patterns and available radiation associated with urban canyons and the energy exchange with the different surfaces of the buildings that form them.

9) *The role of nocturnal chemistry in the formation of aerosols*. The formation of secondary aerosols has been linked to photochemical processes; however, the nocturnal chemistry dominated by the NO_3 radical can be an important source of secondary nitrated compounds and precursors for diurnal chemistry. It is necessary to carry out studies that evaluate the participation of dark reactions in the formation or transformation of aerosols, as well as to understand the mechanisms involved in the formation of reactive species such as HONO.

4.3. Characterization of gases and particulate matter in the Megalopolis

International experience indicates that effective environmental management requires significant investments in scientific research, including ambient air quality monitoring and special field measurement campaigns, which are essential to provide the information needed for air quality modeling and forecasting (Velasco et al., 2021).

Air quality management in the MCMA has benefited when those in charge have teamed up with national and international scientists to better understand the chemical and physical processes behind air pollution. Information obtained from scientific studies, including the Integrated Assessment of Mexico City Air Quality conducted by MIT (Molina and Molina, 2002), and the intensive field measurement campaigns, IMADA-AVER 1997 (Doran et al., 1998; Edgerton et al., 1999), MCMA-2003 (Molina et al., 2007), and MILAGRO 2006 (Molina et al., 2010), provided comprehensive information on the emissions and the transport and transformation of the pollutants in the MCMA atmosphere, and significantly improved the knowledge of the meteorological and photochemical processes contributing to the formation of O_3, secondary aerosols, and other secondary pollutants. The key scientific findings and policy implications were incorporated into current air quality management programs. Although government agencies, university researchers and independent researchers have carried out some special studies, relatively few field studies have been conducted in the MCMA and other regions of the Megalopolis since the MILAGRO campaign.

Below is a brief description of the scientific research carried out in the last five years about atmospheric pollution in the Megalopolis. This summary is not intended to be an exhaustive review, but it does seek to provide an overview of the studies carried out in the region that have been published in scientific journals, or presented in technical reports from the government and other research institutions. Studies related to the impact of lockdown on air quality during COVID-19 pandemic is presented in Section 4.7.

4.3.1. Volatile organic compounds

The important role of VOCs in atmospheric chemistry, especially in the formation of secondary species, was previously described. The complexity of VOCs in the MCMA was comprehensively investigated during the MCMA-2003 and MILAGRO 2006 campaigns using wide-ranging measurement methods deployed at background, source, and downwind sites, as well as at rural, suburban, and industrial sites (see Velasco et al., 2007; Jobson et al., 2010; De Gouw et al., 2009; Fortner et al., 2009; Apel et al., 2010; Bon et al., 2011). The results showed that liquefied petroleum gas (LPG) use was an important source of low molecular weight alkanes, while evaporative fuel and industrial emissions, as well as the use of solvents, and the application of coatings and paints were important sources for aromatic VOC and methanol in the basin (Velasco et al., 2005, 2009). The two most important VOC species measured in terms of OH reactivity were formaldehyde and acetaldehyde; aldehydes were major components of the outflow reactivity. Analysis of the huge data sets provided a much better understanding of the sources and atmospheric loadings of VOCs in the MCMA and highlighted the urgent need to include continuous VOCs monitoring as part of routine air quality monitoring programs.

According to the 2018 emissions inventory for the MCMA (SEDEMA, 2021), area sources are the main emitter of VOCs and toxic compounds. More than 30% of VOC emissions are due to the commercial and domestic use of solvents in everyday consumer products and about 20% from leaks at LPG facilities (see Chapter 3, Section 3.3). Given the important role of VOCs, not only that it is important to continue monitoring them, but it is also essential to reduce their emissions by implementing effective emission control technologies and strengthening regulatory measures. This is discussed in more detail in Chapter 6.

In the case of Mexico City, which has a problem of secondary pollution, monitoring should be carried out at least during the O_3 season each year to generate the input data for modeling studies and the information required to implement control measures. Considering the relevance of secondary aerosols in the net loading of atmospheric particles in the city, periodic monitoring should also be carried out during the winter period when particle pollution is at its worst.

In the Megalopolis, the Environmental Analysis Laboratory of the Air Quality Monitoring Directorate of Mexico City’s Secretariat of the Environment (SEDEMA, *Secretaría del Medio*

Ambiente) has the capacity to carry out continuous monitoring of hydrocarbons (C2 to C12) based on gas chromatography (SEDEMA, 2016). However, previous efforts to install permanent continuous monitoring have been hampered by lack of adequate budget. Measurements have been limited to some field campaigns financed with resources from other sources and by personal efforts of independent researchers for limited periods. On the other hand, after the O_3 pollution events that occurred in 2016, SEMARNAT granted resources to INECC to provide infrastructure for the continuous monitoring of hydrocarbons to support the entities of the Megalopolis in the study of atmospheric chemistry. However, currently they lack the resources to undertake medium- and long-term campaigns. Some research institutions such as the UAM-A and the ICAyCC-UNAM have installed capacity to measure VOCs by continuous methods or by analyzing collected samples; however, their measurements are generally limited to short-term measurement campaigns, providing only a snapshot of the situation with limited information to meet management needs. In recent years, VOC measurements have been scarce and, outside of Mexico City, only the INECC has made efforts through isolated projects to carry out measurements in other cities of the Megalopolis

The Air Quality Monitoring Directorate (DMA) of SEDEMA carried out measurement campaigns in 2012, 2014- 2018 during the ozone season. However, the processing and analysis of the data derived from the measurements from 2014 to 2018 was carried out later with the selfless collaboration of specialists from outside the institution. The data obtained have provided inputs to advance the study of atmospheric chemistry in Mexico City (for example, Jaimes-Palomera et al., 2016; Zavala et al., 2020, Akther et al., 2023).

4.3.1.1. Recent changes in O_3 production and VOC reactivity

Zavala et al. (2020) investigated the changes in O_3 production and VOC reactivity using VOC data measured in 2014-2018 and compared with the corresponding O_3 production estimates from the intensive field campaigns conducted in MCMA-2003 and MILAGRO-2006 (Molina et al., 2007; 2010; Lei et al., 2007, 2008; Song et al., 2010). The results indicated that the spatial distribution of VOCs was heterogeneous within the MCMA, where concentrations at sites located on the periphery were generally lower than those within the city core. Variations during the day were determined by the evolution of the mixed layer, anthropogenic activities, and photochemical activity. Significant decreases were observed in the levels of ethene, benzene, and toluene, with respect to MILAGRO, which is consistent with the reduction that has been observed in VOC emissions from mobile sources. The use of LPG continued as the main source of propane and butane in the city; although an increase in propane was observed since 2006, the sum of butane and isobutane concentrations did not show changes. At urban sites, the average concentrations of ethylene, benzene, and toluene decreased by 2.2, 2.6, and 3.5 times in 2014-2016 compared to the values reported in 2006, respectively. In contrast, the sum of other aromatic compounds such as ethylbenzene, m,p,o-xylene and 1,2,4-trimethylbenzene have not decreased in the same proportion. In the case of isoprene, association with vehicle exhaust was observed; however, the possible presence of biogenic contribution was detected during the warm season.

The study reported a reduction of VOC-OH reactivity at the monitoring sites located in the urban core during the morning rush hour but remained relatively constant in the northern and southern outskirts. Evaluation of the reactivity of VOCs and the behavior of O_3 and NO_X in the metropolitan area suggested an important spatial heterogeneity in the production of O_3, which implies spatially different VOC and NO_x sensitivity regimes (see Figure 4.3). The study also found significant increases in NO_2/NO ratios, suggesting changes in the pathways for the nighttime accumulation of HO_x radicals and NO_y species, which could affect the morning photochemistry and radical budgets for secondary aerosol formation.

Results from this study suggest that emission controls should consider spatial variability in atmospheric reactivity and in O_3 production across the city. A robust, spatially representative, and continuous database of VOCs observations, including oxygenated volatile species related to cleaning and personal care products, is needed to assess the impacts of emission control strategies. The results can serve as the basis for new focused field measurements to better understand changes in the atmospheric chemistry of the MCMA and the Megalopolis region, and to support comprehensive modeling studies for the design of effective emission control strategies in the Megalopolis.

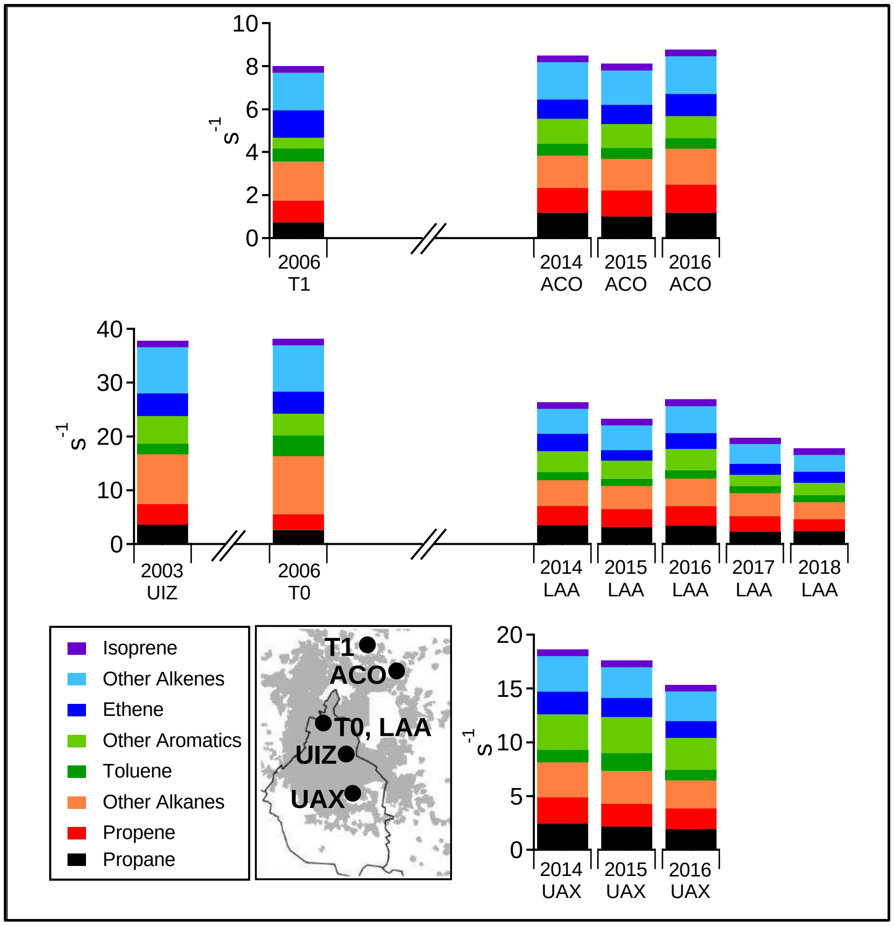

Figure 4.3. VOC-OH reactivity during the morning peak hour (6:00–9:00 AM) by groups, at monitoring sites T1, T0, Acolman (ACO), Environmental Analysis Laboratory (LAA), UAM Xochimilco (UAX) and UAM Iztapalapa (UIZ) from 2003 to 2018. Isoprene data for UAX in 2016 were not available, so the 2015 average isoprene concentration was used instead. The lower map shows the location of the sites of monitoring within the MCMA. (Source: Zavala et al., 2020).

4.3.1.2. VOC profiles from light-duty gasoline vehicles

In 2018, Mugica-Álvarez et al. (2020a) carried out a VOC-sampling campaign inside and outside of two tunnels in Mexico City aiming to update the exhaust and evaporative emissions profiles from light-duty gasoline vehicles. The results from one of the tunnels were compared with similar measurements conducted in 1998. They also measured the composition of gasoline and evaporative emissions (Mugica-Álvarez et al., 2020b). Mugica-Álvarez et al. (2020a) found a 77% decrease in VOCs levels in 2018 in ambient air compared to 1998 measurements. Aromatic and olefin contents in exhaust emissions decreased over the 20-year period from 26 to 17% and from 16 to 12%, respectively, while the content of acetylene, a marker of gasoline combustion, decreased from 8 to 4%. Alkanes dominated the mass composition of VOCs in ambient air with 77% due to the presence of species associated with LPG. The most abundant VOCs in the exhaust emissions were butane, isopentane, toluene and ethylene, and in general, the concentrations of toxic VOCs such as benzene, toluene and xylenes decreased in 2018 compared to 1998 as a consequence of the modifications in vehicle technologies and gasoline composition. The O_3 formation potential of all the VOCs analyzed was determined in both exhaust and evaporative emissions. A reduction in the reactivity of VOCs against OH was observed in 2018 compared to 1998; the most reactive compounds in the exhaust emissions in 2018 were ethylene, propylene, xylenes, and toluene, while 4-methyl pentane, isopentane, 2-methylpentane, and xylenes were the most reactive in evaporative emissions.

Mugica-Álvarez et al. (2020a, 2020b) found that the Magna and Premium gasolines had the same content of olefins and oxygenated compounds; however, Magna gasoline had a higher content of alkanes, isoalkanes and naphthenes compared to Premium gasoline, while Premium gasoline had higher content of aromatic compounds relative to Magna. The profile of evaporative emissions was different from that of the exhaust emissions and, although they contain a third of the aromatic compounds present in the exhaust emissions, they had more than 10% olefins that could affect O_3 production. Analysis of 30 gasoline samples over a two-year period showed that the composition of Magna and Premium is the same at all service stations, despite the presence of different brands of gasoline, presumably because all gasolines were distributed by PEMEX.

Results from the tunnel studies of VOCs demonstrated that transport-related measures implemented in the last 20 years have been successful in improving the air quality in the MCMA; however, the aromatic and olefin content in gasolines needs to be further reduced to lower the concentrations of toxic and reactive species. Furthermore, it is important to control gasoline vapors, both in vehicles and in the service stations, since they are emitted continuously and do not depend on the vehicle circulation, but on the ambient temperature and the composition of the fuel.

4.3.1.3. VOC measurements during COVID-19 pandemic

Between December 2019 and May 2021, the INECC carried out VOC measurements at some sites in the State of Mexico and Mexico City using a mobile unit equipped with gas chromatography (Blanco Jiménez et al., 2022). In the State of Mexico, measurements were carried out in the Toluca Center (December 3 to 13, 2019) and in the Aragón Faculty of Higher Studies (FES Aragón) (December 20, 2019, to January 12, 2020), Villa de las Flores, Coacalco (May 12 to 23, 2021). In Mexico City, measurements were carried out in the Viveros de Coyoacán, where the INECC laboratory is located, during two measurement campaigns (April 27 to June 15, 2020, and February

12 to April 12, 2021). However, the result has not been published yet. It is anticipated that these results from the INECC measurements, some taken during the lockdown period of the COVID-19 pandemic when the emissions were significantly reduced, will be important for comparing with subsequent measurements.

4.3.1.4. Other VOCs-related studies

Akther et al. (2023) used VOC data, aerosol ionic composition, criteria pollutants, surface meteorological data, and continuous measurement of planetary boundary layer height at an urban site in Mexico City to explain the increase in O_3 during the March 2016 severe pollution episode. The study evaluated the contrast between two different atmospheric scenarios that occurred consecutively, where meteorology played a relevant role. The first scenario (March 8-11) was characterized by atmospheric instability, efficient dispersion, and low levels of atmospheric pollutants; in the second (March 12 to 18), an intense and prolonged condition of atmospheric stability favored an active photochemical production and the accumulation of pollutants in a multi-day pollution event, triggering one of the worst O_3 pollution events in the previous decade. They observed important changes in boundary layer height, as well as evidence of recirculation and precursor accumulation during the event. Applying the positive matrix factorization (PMF) method, they were able to identify four factors associated with VOCs and aerosol emission sources: (1) secondary aerosol precursors, (2) combustion and evaporation of fuels, (3) geogenic source and (4) vehicle exhaust emissions, with contributions of 11.9, 30.2, 9.1 and 48.8%, respectively. According to the reactivity analysis, isoprene and ethylene were identified as the VOCs that had the highest potential for oxidation and O_3 formation at peak times, during the period prior to the O_3 event (March 8 to 11), while during the same time period for the O_3 episode (March 12 to 18), the m,p-xylene were added to ethylene as the most relevant in photochemical processes. This study highlights the relevance of meteorology as a determining factor during O_3 pollution events, as well as the impact that the composition of VOCs can have on O_3 production.

Currently, the Laboratory of Chemical Speciation of Atmospheric Organic Aerosols (LEQAOA, by its acronym in Spanish) at ICAyCC-UNAM is measuring VOCs in the gaseous phase of aerosols using a proton transfer reaction coupled to time-of-flight mass spectrometry (PTR-ToF-MS); however, the result has not yet been published.

4.3.2. Reactive atmospheric nitrogen compounds

Nitrogen plays an important role in air quality and climate change due to the involvement of various nitrogen-containing compounds in atmospheric chemical and physical processes. As shown in Figure 4.1, the interaction and conversions among different nitrogen-containing species, including NOx, HNO_3, HONO, PAN, NO_3, and NH_3, are essential in the formation and destruction of O_3 and particulate matter. Much of our understanding of the sources and processing of these compounds in the MCMA was provided from the MCMA-2003 and MILAGRO campaigns (Molina et al., 2007, 2010). Few studies have been undertaken since MILAGRO. The following describes some of the recent measurements carried out in the MCMA and the surrounding area.

4.3.2.1. Nitric acid

Nitric acid (HNO_3) is mostly of secondary origin and is formed during photochemical processes in the atmosphere of homogeneous phase reactions between NO_2 and the OH radical (see Figure

4.1). It is an important precursor of secondary organic aerosols and acid rain. Despite its importance, measurements in the atmosphere of Mexico City and other cities in the Megalopolis are limited. Continuous measurements of HNO_3 carried out during the MILAGRO campaign reported an average concentration of 1.81 µg/m^3 (Fountoukis et al., 2009). The measurements made during the AERAS 2015 campaign (AERosoles AtmosféricoS), carried out by the Atmospheric Monitoring Directorate in 2015 (November 2015 to March 2016), reported an average value of 1.0 µg/m^3 (Retama & Velasco, 2022). In the atmosphere, HNO_3 is rapidly neutralized by ammonia to form NH_4NO_3, which rapidly dissociates into its precursors with increasing temperature (Fountoukis et al., 2009). About 32% of the total nitrate is in the particulate phase (Retama & Velasco, 2022). As expected, the highest concentrations of HNO_3 were generally observed in the early afternoon, when the temperature reached its maximum.

4.3.2.2. Nitrous acid

Nitrous acid (HNO_2 or HONO) is a common compound in the atmosphere of Mexico City and an important source of OH radicals. It can be formed in the homogeneous phase of the reaction between the OH radical and NO, but also from heterogeneous phase reactions on urban surfaces and from aerosols (see Figure 4.1). It photodissociates easily in the presence of sunlight; therefore, its highest concentrations are usually observed at night. HONO is the main initiator of photochemical activity in the early morning hours (Volkamer et al., 2010). As in the case of HNO_3, measurements of HONO are scarce. The first measurements of HONO were made during the MCMA-2003 and MILAGRO campaigns (Molina et al., 2007, 2010). As part of a study to evaluate the impact of pyrotechnic activity in air quality, Retama et al. (2019) reported an average concentration of 2.5 ± 1.8 µg m^{-3} for the winter holiday season of 2013-2014. A year later, Retama & Velasco (2022) reported an average concentration of 2.7 ± 2.4 µg m^{-3} corresponding to the November 2015 – March 2016 period.

4.3.2.3. Ammonia

Ammonia (NH_3) is the main basic species in the ambient air of Mexico City. Previous studies identified that the city's atmosphere is abundant in NH_3 (Moya et al., 2001, 2004; San Martini et al., 2005; Fountoukis et al., 2009). The abundance of this compound promotes the formation of secondary aerosols from the neutralization of acid species (for example., HCl, HNO_3, H_2SO_4). There are few measurements of this pollutant, and little is known about its main emission sources. During the AERAS 2015 campaign, an average NH_3 concentration of 7.7 ± 4.0 µg m^{-3} was reported (Retama & Velasco, 2022), which represented around 81% of the total ammonium ($[NH_3]$ (g) + $[NO_3^-]$).

Recently, data from surface-mounted remote sensing or satellite platforms have been used to quantify NH_3 and observe its spatial and temporal variability. Using observations in the atmospheric column obtained with two Fourier-Transform Infrared (FTIR) spectrometers, Herrera et al. (2022) estimated mean values of $14.6x10^{15}$ molecules cm^{-2} and 1.87×10^{15} molecules cm^{-2} for the total column concentration over an urban site and a remote site (Altzomoni) during 2012 and 2020. At the urban site, the presence of NH_3 was related to local emission sources, while contributions from urban and regional emissions (that is, biomass burning and agriculture) were observed at the remote site. A marked seasonal variation was observed with the highest values in the hottest months of the year, April and May.

Satellite observations obtained from the IASI (Infrared Atmospheric Sounding Interferometer) sensor identified that the main sources of NH_3 in the MCMA were in the most urbanized areas of Mexico City and the State of Mexico (Herrera et al., 2022). High concentration of NH_3 was consistently reported in the northeastern section of Mexico City, which coincided with the presence of possible sources of NH_3 such as the International Airport of Mexico City, the Bordo Poniente composting plant, discharge bodies of wastewater, wastewater treatment plants and the agricultural area of Texcoco. Measurements from the surface-based devices were greater than the data from satellite sensor.

4.3.2.4. Peroxyacetyl nitrate

Peroxyacetyl nitrate (PAN, $CH_3C(O)OONO_2$) is a ubiquitous chemical species present throughout the global troposphere. It was first identified as a component of Los Angeles photochemical smog in the 1950s formed by the oxidation of reactive hydrocarbons in the presence of NO_2. It is a powerful respiratory and eye irritant and can damage agricultural crops. A unique property of PAN is that it is highly stable at cold temperatures and can easily decompose, releasing NO_X at warm temperature, thus acting as a carrier and a reservoir of NO_X in remote atmosphere. Modeling studies of O_3 formation during MCMA-2003 indicated significant outflow of pollutants such as O_3 and PAN from the urban area to the surrounding regional environment (Lei et al., 2007; 2008). This result was corroborated by aircraft observations and modeling studies conducted during the MILAGRO campaign (Song et al., 2010). Using novel interpolation of aircraft observations through kriging, in conjunction with model products, Mena-Carrasco et al. (2009) found that long-range export of reactive nitrogen from Mexico City took place primarily via the formation of PANs, in agreement with aircraft observations. PANs can thermally decompose on the regional scale providing a source of NOx and produce additional O_3 further downwind of Mexico City. Thus, outflows of pollutants in the MCMA may affect the ambient air quality and photochemistry on a regional scale.

Marley et al. (2007) measured PAN during MCMA-2003 field study and compared it with similar measurements obtained earlier during the IMADA-AVER campaign in 1997 (Gaffney, 1999). The concentration of PAN in 1997 was found to reach a maximum of 34 ppb with an average daily maximum of 15 ppb, while the PAN levels in 2003 were recorded to have an average daily maximum of 3 ppb. This dramatic reduction in PAN levels observed in 2003 was attributed to the reduction of reactive hydrocarbon emissions due to controls on olefins in LPG, and also due to the significant number of newer vehicles with catalytic converters replacing older, higher emitting vehicles.

Carrasco-Mijarez et al. (2020) measured PAN and NO_2 during two short campaigns in June and October of 2017 using a gas chromatography-luminol detection method in southwest Mexico City. The maximum and hourly average mixing ratios of PAN were 5.2 and 1.3 ppbv in June, and 3.3 and 0.6 ppbv in October, respectively. These mixing ratios were slightly lower than those reported in 2003 (Marley et al., 2007), suggesting that PAN precursor levels have only partially decreased during the 15-year period. PAN maintains a diurnal pattern similar to that of O_3 with maximums in the mid-afternoon and minimums during the night, with a relatively high background concentration in the nighttime period associated with the stability of the compound at lower temperatures.

4.3.3. Particulate matter: sources, composition, and properties

4.3.3.1. Composition and size distribution of particulate matter

Despite the high levels of PM, their demonstrated impacts on human health and the need for data for management, there are few recent studies on PM in the Megalopolis region. Most of the published works correspond to those resulting from MCMA-2003 and MILAGRO 2006, which utilized multiple measuring platforms, instrumentation, and data analysis techniques to obtain comprehensive information about the sources and processing of primary and secondary PM and their impacts on air quality and climate (see Molina et al., 2007, 2010 and the references therein).

The identification of urban emission sources and the characteristics of primary particles is relatively simple compared to the identification of the origin and destination of secondary particles. Thermodynamically speaking, there is a dynamic relationship between the composition of the particles and the gas phase in which they are suspended, therefore, the characterization of particulate matter requires the study of both phases of the aerosol.

The MCMA-2003 and MILAGRO-2006 field measurement campaigns have provided extensive knowledge of the composition, size distribution and atmospheric mass loadings of both primary and secondary fine particles, and an improved understanding of the evolution and the radiative properties of aerosols (Molina et al., 2007; 2010). Between 2013 and 2015, Mexico City government, through SIMAT, acquired online analytical instrumentation to elucidate the chemical composition of particles following the findings from MCMA-2003 and MILAGRO. As already mentioned, the lack of adequate financial resources and trained personnel keeps equipment under-utilized. Thanks to the dedication of the specialists outside the institution who, with their own financial resources and time, have made appropriate use of such equipment, benefited Mexico City's air quality management, as well as shared their results with the scientific community through peer-reviewed journals (for example, Retama et al., 2019, 2022).

According to the most recent measurements, the concentration of $PM_{2.5}$ has decreased relatively little in the last 20 years on average, and none during the last decade despite being one of the priority pollutants in management plans (SEDEMA, 2020). The composition of PM in Mexico City was dominated by the presence of organic matter, representing more than 50% of the total mass of the particles (Salcedo et al., 2018; Retama & Velasco, 2022). Particles of secondary origin dominated the PM composition, mainly during late morning and early morning when solar radiation was intense, while particles of primary origin were more abundant at the beginning of urban activity (Retama and Velasco, 2022). In terms of size, $PM_{2.5}$ was dominated by submicron particles (diameter < 1 µm), which represented 70% or more of its mass (Retama et al., 2022).

As shown in Figure 4.4, the composition of the particles changes throughout the day depending on the temperature, humidity, and the oxidative capacity of the atmosphere; for example, volatile compounds, such as ammonium nitrate (NH_4NO_3), ammonium chloride (NH_4Cl), and some compounds in the organic fraction, are in thermodynamic equilibrium with their components in the gas phase. These changes in composition are also reflected in its properties (Retama et al., 2022).

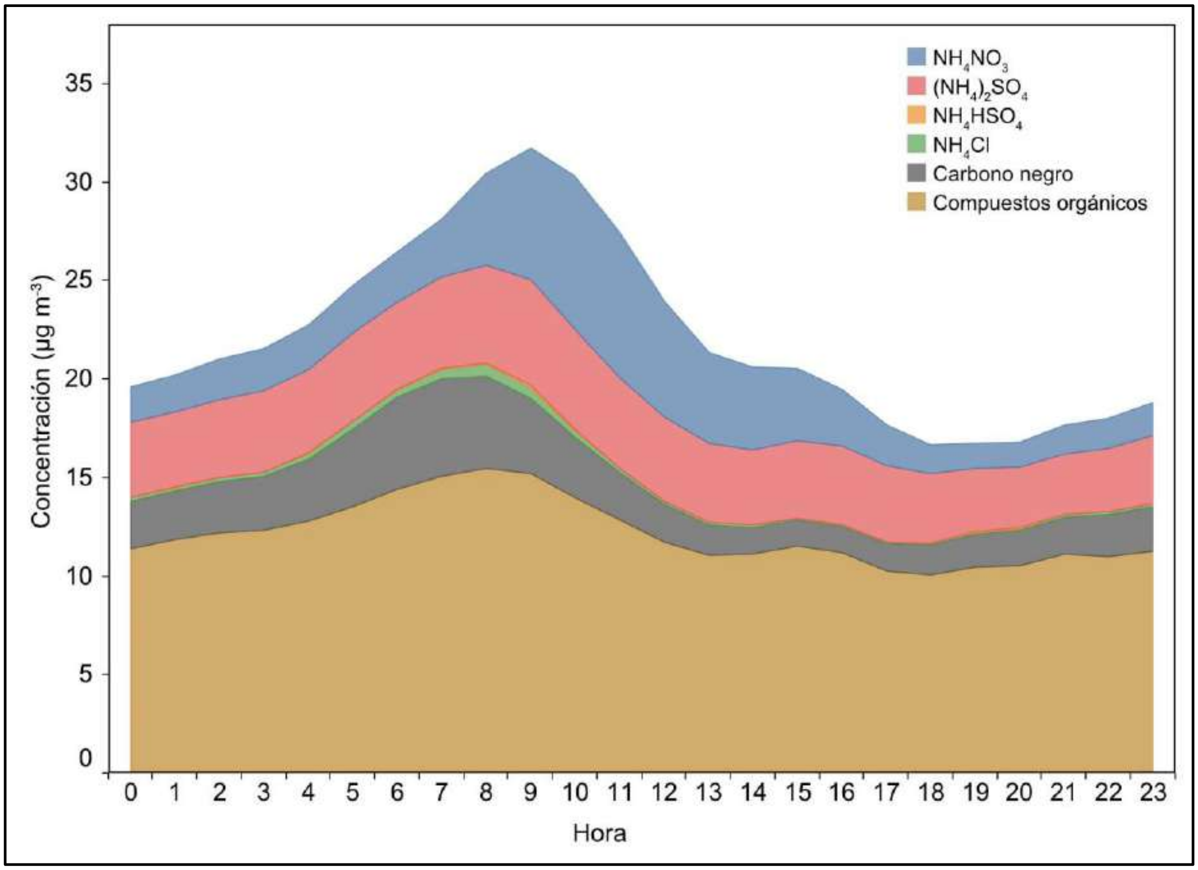

Figure 4.4. Average composition of the PM_1 speciated fraction throughout the diurnal course. (Image prepared with data from Retama et al., 2022).

After organic compounds, the most abundant species in PM_1 included nitrate (NO_3^-), black carbon (BC), sulfate (SO_4^{2-}), and ammonium (NH_4^+) (see Figure 4.5). Other components were found in a lower percentage and include chloride (Cl^-), elements of geogenic origin, heavy metals, and material of biological origin. Black carbon has a primary origin and comes mainly from the burning of biomass at regional scale, and vehicle emissions and the use of firewood and charcoal in the ubiquitous street food stall across the city at local scale. The NO_3^- and SO_4^{2-} are of secondary origin and result from the oxidation of nitrogen and sulfur oxides, respectively. The NH_4^+ in the particles comes mainly from the neutralization reactions of gaseous NH_3 with sulfuric (H_2SO_4), hydrochloric (HCl) and nitric (HNO_3) acids present in the atmosphere. The compounds NH_4NO_3 and NH_4Cl decompose easily with increasing ambient temperature, therefore, their abundance in the particles is modulated as temperature rises during daytime, and according to climatological seasons. Ammonium sulfate ($(NH_4)_2SO_4$) is more stable in ambient temperature range; therefore, it exhibits little variability during the day (see Figure 4.5).

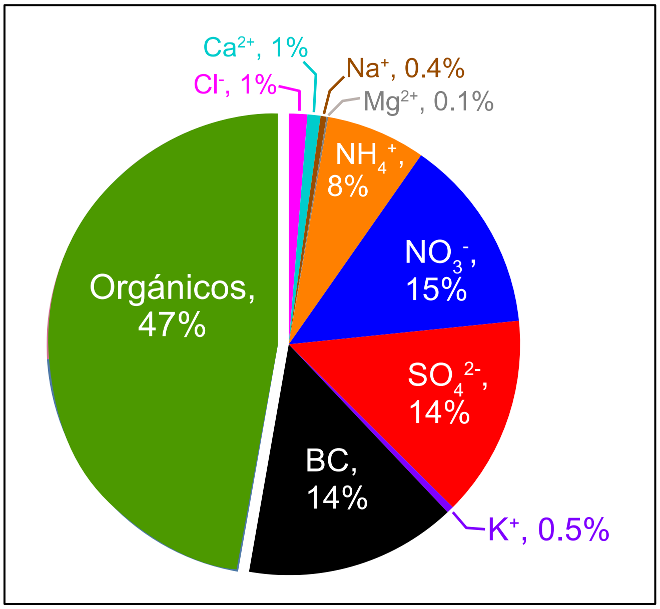

Figure 4.5. Percentage composition of PM_1 in the north of Mexico City. (Source: Retama & Velasco, 2022).

Particles in Mexico City are acidic with a pH value of ~3.3 (Hennigan et al., 2015; Salcedo et al., 2018; Retama & Velasco, 2022), and the abundance of NH_3 in the atmosphere prevents them from reaching lower pH values. Acidity plays an important role in the properties of aerosols, since it increases the solubility of metals, influences the production of organic aerosols and can increase the toxicity of the aerosol.

The study by Salcedo et al. (2018) showed that there are spatial differences in the aerosol composition. The results of the analysis of the composition in a site located in the southern part of the city indicated a higher percentage of organic aerosols and SO_4^2 with lower volatility (more oxidation) in the submicron fraction compared to similar measurements in the north of the city from previous studies (Aiken et al., 2009; Guerrero et al., 2017), suggesting greater aging (greater oxidation) in southern aerosols. Amador-Muñoz et al. (2011) previously identified a spatial variability in the composition of the organic fraction, with primary contributions in the northwest and southeast of the city, and a higher proportion of secondary organic compounds in the northeast, center, and southwest; with the least oxidized organic aerosols in the northeast and the most aged organic aerosol in the southwest.

The organic fraction is made up of a complex mixture of compounds with diverse origins. An important fraction is of the primary type; however, the majority comes from the oxidation of VOCs in the atmosphere since the photochemical processes generally result in the formation of particles. The most recent studies available for Mexico City indicate that primary organic compounds represent around 20-35% of the mass of the organic fraction, while the secondary fraction represents between 65-80%, depending on the location in the city (Salcedo et al., 2018; Retama et al., 2022). Biomass burning is an important source of organic aerosols and can originate primarily from agricultural and forest fires, but also from the burning of garbage and the use of firewood and charcoal as fuel in street food stalls and for heating. The most important source is forest fires, therefore, their contribution to the particle budget will depend on the frequency and intensity of fires in the region and on the meteorology. In two recent works, contributions between 12 and 15% to the organic fraction were identified (Retama et al., 2019, 2022). During the dry season, agricultural burning and forest fires are a regular source of organic gases and aerosols. In May 2019, Mexico City was under the influence of a plume of pollutants from forest fires in the states located to the west and south, leading to a significant increase in $PM_{2.5}$ concentrations, an enrichment in the organic fraction and a severe impact on visibility (Carabalí et al., 2021; Retama et al., 2022).

In 2018, SEDEMA Atmospheric Monitoring Directorate acquired an organic aerosol thermal desorber coupled to a gas chromatograph with a mass spectrometry detector (TAG-GC-MS) to measure primary and secondary components present in the particulate phase of the aerosol with high temporal resolution and high specificity. This instrument will improve the characterization of organic components, the diurnal and nocturnal chemistry involved in the formation of secondary aerosols, and identification of emission sources. Figure 4.6 shows an example of the data obtained from this instrument.

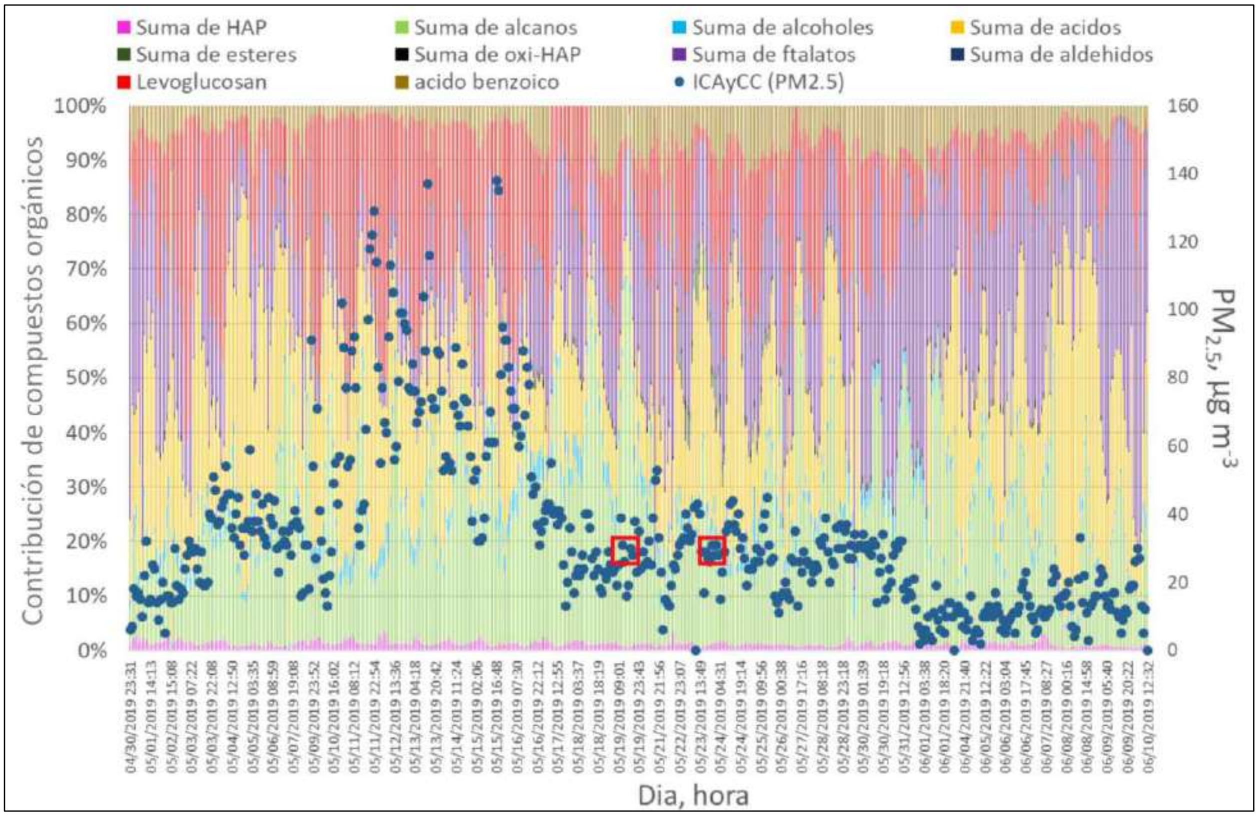

Figure 4.6. Hourly time series of 110 organic species grouped into 9 categories (color bars) contained in $PM_{2.5}$. The time series correspond to a test period of 52 days (May-June 2019) caried out in which the capacity of the TAG-GC-MS to improve the chemical speciation of organic aerosols in the atmosphere of Mexico City, was evaluated. Blue circles refer to $PM_{2.5}$ concentrations, the red boxes show two events with the same concentration of $PM_{2.5}$ but different composition. (Source: Amador-Muñoz et al., 2022b).

The TAG-GC-MS has been employed in some recent measurement campaigns south of Mexico City and in Tula, Hidalgo. In Mexico City, the preliminary results of the first Chemical Speciation of Atmospheric Aerosols campaign (EQAA1, *Especiación Química de Aerosoles Atmosféricos*) carried out between November and December 2018, have provided the composition and temporal variability of polycyclic aromatic hydrocarbons (PAHs) at a higher temporal resolution. The findings confirmed previous observations by Amador-Muñoz et al. (2020, 2022a). The carcinogenic PAHs showed diurnal variability with two maximums, one in the morning (7:00-8:00 h) and another at night (21:00 – 22:00 h); this variability was similar to that observed in CO and NO_X related to vehicular traffic. The recurrent presence of retene (7-Isopropyl-1-methylphenanthrene), associated with southwest wind flows, mainly during the nighttime suggested the contribution of aerosols derived from wood burning, possibly due to the use of wood in cooking and domestic heating in the mountainous area of Ajusco. Preliminary results from the second Chemical Speciation of Atmospheric Aerosols (EQAA2) campaign (Amador-Muñoz et al., 2022c), conducted between May 1 and June 10, 2019, identified the abundant presence of the biomass burning tracers levoglucosan and retene, during the severe pollution episodes related to regional biomass burning emissions transport in May 2019. During this pollution event the ineffectiveness of the Double-Today-No-Circulate (*Doble-Hoy-No-Circula*) program to reduce particulate matter levels was verified. Although the analysis of the data obtained in the campaigns described is still in process, the preliminary results illustrate the potential of the instrument to advance knowledge about aerosols, their composition, and impacts.

Currently, a study is being developed to characterize both phases of the aerosol using a set of state-of-the-art instruments and techniques, deployed in the Laboratory of Environmental Analysis of the Air Quality Monitoring Directorate. The main objective is to characterize the organic and inorganic composition of the particulate and gaseous phases with high temporal resolution, as well as the optical properties of the aerosols, and from the data to investigate the formation processes of secondary aerosols in the area. The measurement campaign was carried out between April and May 2022, the first results will be available in 2023. The preliminary results show the strong impact that the combustion and/or evaporation of diesel has in this area, especially of vehicular origin. The concentration of phenanthrene, considered a marker of this source, is at least 10 times higher than that observed in the south of Mexico City during the EQAA1 campaign. In addition, the data also suggest that the dominant family of compounds that make up the organic fraction determined in the EQAA2 campaign are saturated and unsaturated fatty acids, which can come from cooking food (among other sources), which is a common activity in Mexico City.

Regarding particle size, there is growing evidence that ultrafine particles (particles smaller than 100 nm in size, UFPs) can cause a variety of severe health impacts. Due to their size, they are capable of translocating into the bloodstream, crossing the nasal/olfactory, respiratory, gastrointestinal, placental and cerebral-blood barriers, and reaching the central nervous and lymphatic systems (Calderón-Garcidueñas and Ayala, 2022). Few studies have been carried out in Mexico City to determine the size distribution and number concentration of UFPs. Caudillo et al. (2020) measured particles between 10 and 400 nm in the autumn of 2016 and found a significant relationship between vehicle emissions and the number concentration of nucleation mode (≤ 50 nm). The diurnal variability in both modes was characterized by the maximum concentration during the morning rush hour, coinciding with maximum CO concentration. In the accumulation mode, increases associated with the formation of secondary aerosols were observed. During a SO_2 pollution event, they found evidence of the possible formation of aerosols by nucleation.

Velasco et al. (2019), while carrying out measurements of personal exposure at the street level, found that pedestrians in Mexico City are exposed to particles with a mean size of 49 ± 20 nm. This figure was derived from the average surface diameter calculated from simultaneous and independent measurements of particle number concentration and associated active surface area.

4.3.3.2. Characterization of major hazardous particulate matter in the Megalopolis

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) are common pollutants in the organic fraction; they are found bounded onto the surface of ultrafine particles, especially in the nucleation mode (< 50 nm in size) and therefore are known as particle-bound PAH (pPAHs). They are abundant in urban microenvironments directly impacted by vehicular exhaust and the burning of biomass or garbage, as well as by cooking fumes, especially of gridded and fried meat. Most PAHs are highly toxic, mutagenic, carcinogenic, and teratogenic. Amador-Muñoz et al. (2020; 2022a) studied the spatial and temporal variation of PAHs in $PM_{2.5}$, covering five sites around the MCMA during three different seasons in 2016-2017. The most abundant PAHs in the metropolitan area of Mexico City include benzo[ghi]perylene and benzo[b], [k] and [j] fluoranthenes, among the heaviest (molecular mass > 216 g mol^{-1}), while the most abundant among the lighter ones (molecular mass ≤ 216 g mol^{-1}) are pyrene, fluoranthene and phenanthrene. These compounds show strong correlations with CO and NO_X at all sites, suggesting similar sources of incomplete combustion.

Comparison of PAH levels in $PM_{2.5}$ in the MCMA measured in 2016–2017 with those determined a decade ago in 2006 (Amador-Muñoz et al., 2011) showed a decrease of 34 ± 9% in carcinogenic PAHs and 60 ± 7% in benzo[ghi]perylene. According to the authors, these results demonstrated that air quality management actions implemented during the 10-year period had a favorable impact on their reduction; however, their presence and concentrations still represent risks to human health (SEDEMA, 2020). A recent study on particle personal exposure found that the ubiquitous street food stalls of the city, in addition to being an important source of BC emission, they are also an important source of pPAHs (Velasco et al., 2019).

Toxic metals

Metals represent a small fraction of the mass of suspended particles; however, some of the metals are known to have a significant toxicity burden for humans. The presence of metals is related to geogenic and anthropogenic sources, among the former are volcanic emissions, marine spray, and eroded soils,; while vehicular traffic, burning of fossil fuels, industrial metallurgical processes, and the burning of waste are examples of anthropogenic sources. In the MCMA, the intensive use of catalytic converter to control the emissions of various polluting gases has led to a significant increase in the platinum (Pt) content in $PM_{2.5}$ (Morton-Bermea et al., 2014). Lead (Pb), a pollutant that in the past was associated with the use of leaded gasoline, has been significantly reduced; however, urban soil dust continues to be enriched with this metal, with levels that could imply some risk for the population (Aguilera et al., 2021). Urban soil dust is also an important source of Pb, zinc (Zn), copper (Cu), chromium (Cr) and nickel (Ni); these metals come mainly from the mechanical wear of vehicles, brake and tires wears, fuel combustion, automotive additives, and the degradation of street painting (Aguilera et al., 2021; Delgado et al., 2019). Geogenic sources had the largest contribution to metal loading in $PM_{2.5}$ and were related to regional transport and the contribution of local geogenic material and/or re-suspension of soil dust (Garza-Galindo et al., 2019). The presence of metals associated with industrial activity was mainly linked to local contributions (Hernández-López et al., 2021).

There are some sources that may have additional sporadic contributions to the metal content in aerosols, such as biomass burning and pyrotechnics, which are an important source of potassium (K) and other metals (Hernández-López et al., 2021; Retama et al., 2019); others, such as the volcanic emissions of Popocatépetl, can be an important source of mercury (Hg) (Schiavo et al., 2020). There is little information on the situation in other urban and suburban areas of the Megalopolis, however, evidence of the presence of metals related to anthropogenic sources has been reported (Gómez-Arroyo et al., 2018; Ramos-H et al., 2020).

Atmospheric pollutants from cremation ovens

Cremation ovens or crematoriums are an emerging urban source of combustion gas emissions, mainly CO and NO_X, and $PM_{2.5}$. In Mexico City there are around 40 public and private crematoriums where an average of around 25,000 cremations are performed annually. A recent study by González-Cardoso et al. (2020) evaluated the emissions of CO, $PM_{2.5}$, elemental carbon (EC), organic carbon (OC) and PAHs, from several cremation ovens representative of those used in Mexico City. The sample of ovens included those with and without air supply control. They found that the furnaces without air supply control tend to generate up to six times more emissions than furnaces with air control. The 5- and 6-ring PAHs (for example, benzo[ghi]perylene and indeno[1,2,3-cd]pyrene) were the most abundant in the air-controlled ovens, while the 4-ring PAHs (for example, fluoranthene, pyrene, and benzo[a]anthracene) were the most abundant in kilns without controlled air supply; carcinogenic species represented 45% of the total PAH. Mercury was the most abundant metal associated with the particles, while the emissions of copper, lead, nickel, and vanadium (V) were higher than those reported for other combustion facilities using diesel, biomass, and LPG furnaces. Although emissions from cremation did not significantly modify the composition and background concentrations of urban aerosols, they could have an impact on nearby areas, mainly due to the increase in PAHs and Hg. This work was used in the design of the Mexico City's local standard for crematoria ovens NADF-017-AIRE-2017.

Emissions from burning of pyrotechnics

The burning of pyrotechnics is an activity deeply rooted in civic and religious festivities in Mexico as well as in many other countries. Fireworks display during celebrations such as New Year's Day around the world, Diwali in India, and Spring Festival in China, substantially increase the level of air pollutants leading to some countries restricting their sales and use (Molina, 2021).

In general, the two most polluted days of the year in Mexico City are Christmas and New Year's Day (CAMe, 2022). Retama et al. (2019) characterized the impact of fireworks and bonfire activity (from burning of tires and wood) on the air quality of Mexico City during the winter of 2013-2014 and found that during the burning of pyrotechnics during Christmas and New Year, small particles of metals and organic and inorganic species were emitted, as well as harmful gases such as SO_2, NO_2, CO and HONO. The stagnant atmosphere at night accumulated the fireworks haze under a shallow boundary layer. By sunrise, once the fireworks activity has stopped, the photolysis of the abundant HONO accumulated throughout the night, leading to rapid production of nitrate (NO_3^-), ammonium (NH_4^+), sulfate (SO_4^{2-}) and secondary organic aerosols. The diurnal particle concentrations were higher than during the nocturnal firework events.

The production of pyrotechnics is an important economic activity in the State of Mexico, particularly in the municipality of Tultepec, where approximately 65% of its population is directly or indirectly involved in this activity. A recent report from the State of Mexico Secretary of Environment (*Secretaría del Medio Ambiente*) highlighted the need to improve the production systems of pyrotechnics and migrate towards technological alternatives that reduce environmental impacts on air quality (EDOMEX, 2021).

4.3.3.3. Bioaerosols

The term bioaerosols refers to all suspended particles of biological origins in the air, including bacteria, fungi, viruses, pollen, and their derivatives such as allergens and endotoxins (Yao et al, 2018). International interests in bioaerosols have increased recently to improve the knowledge on their identification, quantification, distribution, and health impacts. The presence and abundance of aeroallergens, such as pollens and fungal and bacterial communities in air, is an emerging topic of research in Mexico.

With advances in molecular biology in recent decades, the specific detection of bioaerosols collected from the air, mainly fungi, yeasts, bacteria, and archaea, has been achieved using various sampling equipment. Calderón-Ezquerro et al. (2020) employed a metagenomic approach to characterize the bacterial and fungal communities, using 16S rRNA and the internal transcribed spacer region of the nuclear ribosomal RNA. The study took place in Mexico City during the dry season, on days with high levels of O_3 and suspended particles (March 14 to 18, 2016). They observed increases in bacteria and fungi present in the air during the environmental contingency triggered by high O_3 levels, which could possibly cause synergistic effects on human health due to simultaneous exposure to chemical pollutants in the air and the microbiota. In a study on the metagenomic detection of bacteria from the air in Mexico City carried out during an annual cycle in three areas of the city, Calderón et al. (2022) found significant differences in the diversity of bacterial communities, many of the species found have been recognized as pathogens and their presence is associated with climatic seasons and the degree of urbanization, with greater diversity during rainy season and in the more urbanized districts.

The Mexican Aerobiology Network (REMA, *Red Mexicana de Aerobiología*), installed and operated by UNAM starting in 2008, currently has sampling sites in different areas of Mexico City and the State of Mexico. The purpose of the network is to inform the population about the atmospheric concentrations of different pollen allergens, quantify risks to health and ecosystems, and observe the possible effects of climate change on vegetation. The results will allow the evaluation of spatial and temporal variations of atmospheric pollen, in addition to their impact on human health, the development of pollen calendars, and will be useful for forecasting the presence of pollen aeroallergens according to different temperature scenarios. Calderón-Ezquerro et al. (2016) developed the first pollen calendar for Mexico City, which includes a large variety of taxa, many of which show a long main pollen season that can last all year.

The study of bioaerosols is a work in progress, the availability of more sampling sites and new data on their composition and timing will provide more and better evidence that in the medium term could allow the incorporation of this pollutant in air quality management strategies with a focus on protecting the health of an important sector of the population.

4.3.4. Aerosol optical properties

Atmospheric aerosols interact with sunlight and affect air quality and climate. They absorb and scatter light according to the optical properties resulting from their mass loading, size distribution, age, chemical composition, mixing state and hygroscopicity. Therefore, it is necessary to evaluate the optical properties of aerosols along with their chemical composition, origin, seasonal variability, and diurnal photochemistry to mitigate their atmospheric impact, including the visibility deterioration within the city, which despite being the most evident effect of air pollution, it has not received the necessary attention from environmental authorities and academia.

The IMADA-AVER, MCMA-2003, and MILAGRO field campaigns provided valuable information on the optical properties and chemical composition of the aerosols during the spring season under dry and warm weather conditions (Doran et al., 1998, Edgerton et al., 1999, Molina et al., 2007, 2010). Recent studies have determined the optical properties over longer periods using ground-based instrumentation (Retama et al., 2015; Liñán-Abanto et al., 2019), and remote-sensing data (Carabali et al., 2017; Gorchakov et al., 2017), but they have not simultaneously evaluated the chemical composition of the aerosols.

In such a context, Retama et al. (2022) investigated over two years the aerosols' ability to scatter and absorb light in the atmosphere of Mexico City combined with a detailed chemical speciation of their components, focusing on the characteristics of brown carbon (BrC). Brown carbon is the term used when the organic species that give particles a brownish rather than black appearance are considered. The authors found that, depending on the climatological season, 65-74% of the light extinction in the near infrared region was due to scattering. At least half of the light scattering could be attributed to organic aerosols during regular days, and over 80% during wildfire episodes. Nitrates and sulfates were also important contributors to light scattering. The former made a larger contribution on regular days (20%) than during the wildfire season (14%), the opposite was true for the latter (11% and 22%, respectively). Regarding light absorption, fresh particles associated with traffic emissions had a major role on days not affected by biomass burning plumes. During wildfire episodes, the organic fraction contributed up to 50% to light absorption. Aged organic aerosols had a negligible contribution to light absorption, but newly formed secondary organic aerosols contributed on average 24% in days not affected by wildfire plumes. Brown carbon and BC contributed 22% and 78% to the total light absorption in México City, respectively. Brown carbon increases on average 28% the light absorption over that attributed to BC. This increase could be up to 32% during the dry-warm season. In summary, vehicular traffic was the main daily contributor to light absorption, while biomass burning was the major contributor during wildfire episodes. The results of this study updated the findings on the topic achieved during short-term field studies conducted in the past.

4.3.5. Scientific research in the other states of the Megalopolis

There is a geographical bias in the scientific research across the Megalopolis; most of the research studies have been carried out in Mexico City and its metropolitan area. There is little or no e research conducted in the rest of the entities. There are multiple possible reasons behind the lack of scientific research in the other entities, including:

1) Low interest of the environmental authorities in identifying and solving the problem
2) Lack of infrastructure and technical capacity to carry out studies
3) Absence of financial resources to carry out studies
4) Inadequate environmental education that limits the interest of the population in a better air quality
5) Limited availability of air quality data to inform the population
6) Presence or absence of research centers that collaborate with environmental agencies

The monitoring results shows that there are urban areas, apart from Mexico City, with emerging or confirmed evidence of degraded air quality. Despite this, little is known about the origin and characteristics of the pollution, the processes that occur in the atmosphere and the effects on human health. During the severe O_3 pollution events in March 2016, the authorities of Mexico City spoke out about the regional nature of the pollution problem and mentioned that environmental problems were not only the responsibility of the entity, but also a problem that involved emissions generated by neighboring entities, particularly the State of Mexico (see Velasco et al., 2017). The pollution episode marked a milestone in environmental management for the Megalopolis, with positive consequences for the region, since the federal authorities turned their attention to the issue, carrying out an evaluation of the state of air quality monitoring and management in the other entities. This led to the development of a ProAire for the Megalopolis (SEMARNAT, 2017), which includes a scientific research agenda at a regional scale, the release of financial resources for the reinforcement of infrastructure, the strengthening of measurement capabilities of the INECC to support research campaigns in other states, and the involvement of various federal government agencies in the work of the entities.

An example of the regional research is reported by Mora et al. (2017), who studied the behavior of aerosols at the Megalopolis level by analyzing data obtained by satellites, ground measurements, trajectory models, aerosol chemical composition models and reanalysis data for the period 2003 to 2015. The authors found a clear anthropogenic effect on the diurnal and weekday PM profiles, with a notable increase in the levels of coarse particulate matter (diameter ≥ 2.5 µm) during weekday rush hour periods compared to weekends, as well as a statistically significant increase in wind speed and ambient temperature from 2003 to 2015. Among wet deposition species, NH_4^+, SO_4^{2-}, and Ca^{2+} ions correlated best with $PM_{2.5}$ and PM_{10}, suggesting that these species were important components of the aerosol seeding hydrometeors that eventually fell as wet deposition. Among the different species modeled with GOCART, SO_4^{2-} contributed significantly to optical depth (highest in May-June), followed by organics. On the other hand, biomass burning emissions occurred during the dry-hot season (March to May) coinciding with higher values of aerosol optical depth (AOD), the ultraviolet aerosol index (UV AI) and the concentrations of surface particulate matter (PM). Emissions from biomass burning contributed significantly to the high values of AOD, UV AI, and surface PM values in the hot-dry season when the boundary layer was higher.

Although several urban areas in Mexico struggle with maintaining good air quality, little is known about the processes that determine the presence of pollutants in the atmosphere beyond Mexico City. The following describes some results of the scientific research carried out in the other states of the Megalopolis presented during the Virtual Workshop.

4.3.5.1. Tula-Tepeji industrial complex, Hidalgo

Some studies have identified the presence of SO_2 of regional origin in the ambient air of Mexico City (for example, Raga et al., 1999; de Foy et al., 2009). The origin of these emissions has been linked to emissions from the Tula-Tepeji industrial complex (located ~65 km north of the MCMA) and the Popocatépetl volcano (located ~70 km southeast of the MCMA). While the impact of emissions from Popocatepetl depends on volcanic activity and meteorological conditions in the middle atmosphere, emissions from Tula are a continuing source of pollutants in the region. During the MCMA-2003 and MILAGRO-2006 field campaigns, it was shown that these industrial emissions affected the air quality of the MCMA, mainly for SO_2, because the emission rates were higher than those of urban emission sources. However, accurate quantification of the contribution was challenging, since the magnitude of the concentrations and the spatial extent of the impacts depended on the transport patterns of air masses, the meteorological conditions, and the chemical transformation during and after any release event.

The emissions from the Popocatépetl volcano are an important regional source of SO_2 and SO_4^{2-}, according to Arellano et al. (2021), the Popocatépetl volcano emitted an average of 2,115 tons/day of SO_2 into the atmosphere between 2007 and 2016. The contributions of this natural source to pollution in Mexico City are not constant and depend on the frequency and intensity of the emissions and weather conditions.

The Tula industrial complex continues to be a major SO_2 and $PM_{2.5}$ hotspot in the region. It is estimated that in 2017 alone, the industrial complex emitted into the atmosphere approximately 217,200 megagrams (Mg) of SO_2, 89,950 Mg of NO_X, 34,950 Mg of PM_{10}, 23,960 Mg of $PM_{2.5}$, 268,990 Mg of VOCs, and 24,930 Mg of NH_3 (Sosa et al., 2020). The main sources in the industrial corridor include a refinery, a thermoelectric power generation plant and five cement plants. The thermoelectric “Francisco Pérez Ríos” is a thermoelectric plant with a capacity of 2,095 GW with five electricity generating units and with a significant consumption of fuel oil (with 3.5% sulfur content) and natural gas. The thermoelectric plant, together with the "Miguel Hidalgo" refinery, contribute around 80 and 90% of the entity's NO_X and SO_2 emissions, respectively. Since 1989 the region has been classified as a critical zone (ZC, *zona crítica*) in terms of air pollution (ICM, 2021).

In a modeling study on the impacts of SO_2 emissions from the Tula region on the air quality of the MCMA, the measurements of SO_2 and meteorological variables taken during MILAGRO in March 2006 and from a field study in October-December 2008 conducted by IMP, together with long-term RAMA monitoring data and satellite observations, were evaluated to identify the origin and transport of the SO_2 plumes observed in the MCMA (MCE2-INE, 2009). Modeling results showed that the Tula region had higher contributions to surface SO_2 impacts at the MCMA than the

Popocatépetl volcano for the simulated periods. The long-term contribution of volcanic SO_2 emissions to air quality in the MCMA is small, although it could be somewhat more significant in the southeastern part of the city. This result did not exclude the possibility of a greater influence on the city during a volcanic event under suitable transport conditions. The results also suggest that the long-term impacts of the volcano had a greater spatial influence than any local impacts (~60 to 100 km), highlighting the importance of studying the impacts of Popocatépetl volcanic emissions at regional and global scales.

A modeling study, based on MILAGRO data, suggested a contribution of gas venting and flaring activities in Tula to total SO_2 levels of 18% to 27% in the north of the city, and 10% to 18% in the outskirts (Almanza et al., 2012). In a subsequent study, Almanza et al. (2014) estimated contribution of emissions from the Tula industrial complex to the formation of O_3 of between 1 to 4 ppb. However, this contribution could reach 10 ppb in the upper northwest region of the MCMA and the southwest and south-southeast regions of the state of Hidalgo. The O_3 urban plume could reach the northwest of Tlaxcala, the east of Hidalgo and further northeast of the State of Mexico, but with lower values. Furthermore, an estimate of the potential contribution of flaring activities to regional O_3 levels suggested that up to 30% of the regional O_3 originating from Tula could be related to flaring activities. This study also suggested the possibility of "overlooked" emission sources in the region of Tizayuca, Hidalgo, which could have an influence on the air quality of the MCMA. They found that cement plants located in the states of Hidalgo and Mexico could contribute to SO_2 levels in the northeastern region of the Mexico Basin and in the suburban supersite T1 (41%), as well as in some monitoring stations, suggesting that under certain conditions, their contribution could exceed the contribution of the Tula industrial complex.

Between 2006 and 2017, three field measurement campaigns were carried out to evaluate the emissions of NO_2 and SO_2 from the Tula industrial complex: the first in 2006 as part of the MILAGRO campaign using a scanning miniaturized differential optical absorption spectroscopy (Mini-DOAS) (Rivera et al. 2009), the second in 2010, and the most recent in 2017 (Rivera et al., 2022). The results indicated that NO_2 emissions did not show significant changes, while a slight decrease was observed for SO_2 (Table 4.1).

Table 4.1. Results of estimated SO_2 and NO_2 emissions from the refinery and thermoelectric plant of Tula, Hidalgo, during different measurement campaigns.

Year	**SO_2 (ton/day)**	**NO_2 (ton/day)**
2006	384 ± 103	24 ± 7
2010	365 ± 141	23 ± 17
2017	362 ± 300	25 ± 13

Sosa et al. (2020), using a combination of measurements and modelling, identified the increases in SO_2 concentrations in Mexico City observed during the winter, with high emissions at the "Francisco Pérez Ríos" thermoelectric plant in Tula. The authors pointed out that although SO_2 concentrations are not an air quality problem in the MCMA, the presence of acid rain and high levels of sulfates in wet atmospheric deposition remain a cause for concern.

Regarding fine PM, on certain nights, SO_2-rich plumes from the Tula-Tepeji industrial complex arrive in the city and increase the presence of SO_2 and SO_4^{2-}. Therefore, the nocturnal concentrations of both species tend to be similar or higher than those of the rest of the day (Retama & Velasco, 2022). As already mentioned, the vehicles in Mexico City use low-sulfur fuels; therefore, the presence of SO_4^{2-} can be attributed to emissions from the Tula-Tepeji industrial complex.

In addition to the regional contribution to air quality, the industrial corridor has a direct impact on the exposure of the inhabitants of the surrounding communities. However, there is no objective information on the effects of industrial emissions on the health of the population. The organization Iniciativa Climática de México (ICM) carried out a modeling exercise using the AERMOD regulatory model to identify the influence of emissions from the "Francisco Pérez Ríos" thermoelectric plant on SO_2 and $PM_{2.5}$ concentrations in nearby municipalities. Their results identified that the towns of Pradera del Llano, Teocalco, and El Llano to the south of the thermoelectric plant, were in a risk area due to the presence of concentrations outside the maximum permissible limits for $PM_{2.5}$, but not for SO_2 (ICM, 2021).

Recently, the INECC coordinated an intensive short-term measurement campaign in the Tula-Tepeji-Endhó complex to help improve air quality management capabilities in the region. However, the results have not yet been published.

4.3.5.2. Characterization of particulate matter in Queretaro

Olivares-Salazar et al. (2021) described the chemical composition of PM_{10} and $PM_{2.5}$ in the Metropolitan Zone of Querétaro and identify the major emissions sources using positive matrix factorization. The main sources of PM_{10} were resuspension of mineral and construction dust, incineration, industrial emissions, biomass burning and secondary particles. For $PM_{2.5}$, the main sources were resuspension, anthropogenic particles (with incineration and industrial particles), vehicles, and biomass burning. Although some of the sources identified were likely local, the regional contribution to the PM concentrations was significant, thus revealing the importance of studying the central region of Mexico, which is an important industrial and agricultural area.

In another study (Rozanes-Valenzuela et al, 2021), a wind flow climatology was established for the Metropolitan Area of Querétaro (MAQ) by analyzing four years (2014-2017) of back trajectories generated using HYSPLIT model. The results differentiated two flow regimes: one from June to September (rainy regime) and the other from December to May (dry regime). The constant presence of flows from the northeast was observed throughout the year, in contrast, trajectories from the southwest were less frequent and were observed mainly during the dry regime. Some of the observed trajectories to the northeast had their possible origin in a desert region of the state of Querétaro, where several limestone mines were located. During the dry regime and the transition months, some trajectories had a possible origin in the industrial area of Guanajuato, including the Salamanca refinery. This analysis could be useful for identifying regional sources that affect the MAQ and possibly increase its air pollution load.

Liñán-Abanto et al. (2019) studied the optical properties of aerosols at a site north of the MAQ and compared them with similar observations made at the ICAyCC-UNAM, south of Mexico City. They observed a similar diurnal variability in the absorption coefficient at both sites, but with significant differences in magnitude, where the measurements obtained in the MAQ corresponded to a third of the values observed in Mexico City. They observed a coincidence in the hourly profiles of both absorption and scattering coefficients, suggesting similar aerosol sources. They found that air pollution in Querétaro was influenced by local sources (located to the north and south) and by aerosols present in photochemically aged air masses transported regionally and arriving at the city of Querétaro.

4.3.5.3. Air quality monitoring in Puebla

Mora-Ramírez (2022) presented advances in the research work carried out by the Benemérita Universidad Autónoma de Puebla (BUAP), where he evaluated the exposure of cyclists and pedestrians to $PM_{2.5}$ and PM_{10} particles using low-cost sensors, in combination with calibrated scientific instruments. Low-cost sensors were used as an alternative to determine the levels of particles in the central zone of the municipality of Puebla, in conjunction with a project to install monitoring stations. The results highlighted the need for an immediate effort to improve the monitoring network of Puebla and other entities outside of Mexico City, due to the interrelation that exists between the different atmospheric basins of the Megalopolis.

4.4. Urban climatology and air quality

The chemical and physical processes involved in the formation of air pollutants that occur in the atmosphere are sensitive to changes in meteorological conditions. It has been observed that, in urban environments, the warming of the built-up environment and regional climate change are modifying the local meteorology. In terms of air quality, it is known that the increase in temperature can cause an increase in evaporative emissions, impacts on the degradation of pollutant removal processes and the amplification of atmospheric chemistry (Nolte et al., 2018; Fiore et al., 2015; Jacobs and Winner, 2009).

4.4.1. Urban warming and climate change

Structures such as buildings, roads (asphalt and concrete), and other infrastructures absorb and re-emit the sun’s heat more than natural landscapes such as trees, vegetation, and bodies of water. Urban areas, where these structures are highly concentrated and greenery is limited, become “islands” of higher temperatures relative to outlying areas, creating the heat island effects (UHI) (Mills et al. 2021; US EPA, 2022). Heat islands are usually measured by the temperature difference between cities relative to the surrounding areas. The temperature difference between the urban area and the rural surroundings is usually larger at night than during the day and most apparent when winds are weak. Temperature can also vary inside a city; some areas are hotter than others due to the uneven distribution of heat-absorbing buildings and pavements.

The MCMA’s atmosphere has experienced progressive warming in recent decades, possibly because of the synergistic interaction between increased land cover modification, new material used in the construction, anthropogenic heat, and changes in temperature associated with global climate change. According to SIMAT data, in the last 20 years the ambient temperature has increased by ~1.3 ºC (see Figure 4.7). In the case of the State of Puebla, an increasing trend in ambient temperature has also been observed, with an increase of 1.3ºC between 1985 and 2021;

while the precipitation showed an emerging downward trend, with values below the average in the last four years. Continuing warming is expected to worsen in the future. As urban population densities in the Megalopolis increase and natural land areas decrease, heat islands will strengthen. The impacts of urban warming could extend beyond the city's boundaries, altering regional precipitation patterns and modifying aerosol budgets (López-Espinoza, 2022; Aquino-Martínez et al., 2021; Ochoa et al., 2015).

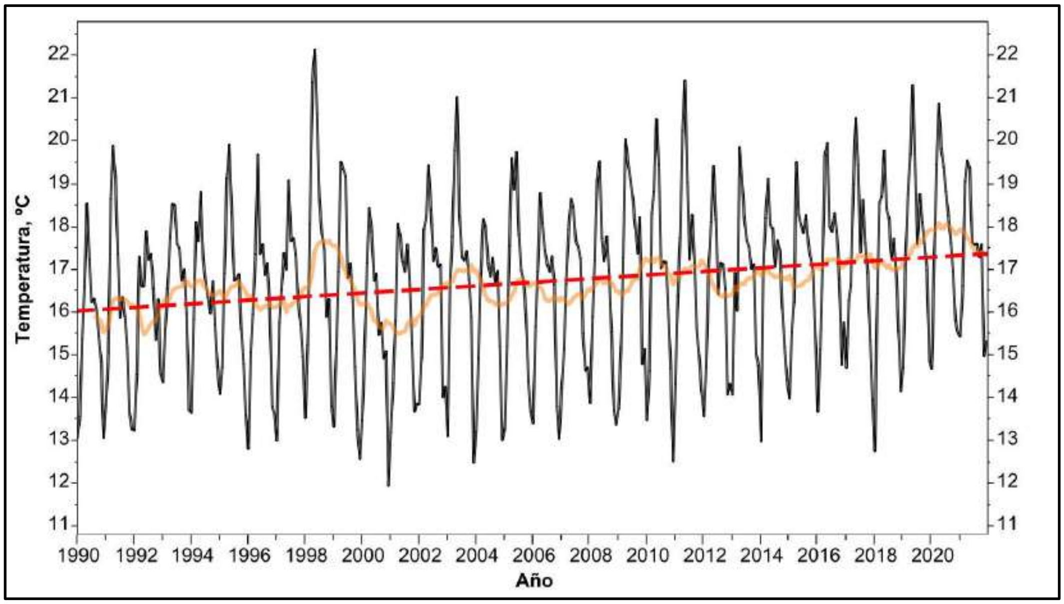

Figure 4.7. Time series of the monthly averages (gray line) obtained from the hourly values at the FAC, MER, MON, PED, SAG, TAH, TLA, VIF and XAL stations operated by SIMAT. The orange line indicates the 12-month moving average, while the dotted red line shows the linear trend. (Author's elaboration with data from: Dirección de Monitoreo de la Calidad del aire, www.aire.cdmx.gob.mx, accessed on September 10, 2022).

The observed increase in the MCMA does not occur in a specific period or season of the year. An analysis of the monthly temperature anomalies confirms that the increases occur in all months of the year, as can be seen in Figure 4.8. It is important to note that in 2019 and 2020 atypical positive anomalies[1] were recorded in all months; interestingly, 2019 and 2020 were among the three warmest years worldwide, suggesting that Mexico City's climate might respond to the global climate changes.

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[1] A temperature anomaly is defined as the deviation (positive or negative) from the average temperature during a certain reference period, often called the base period.

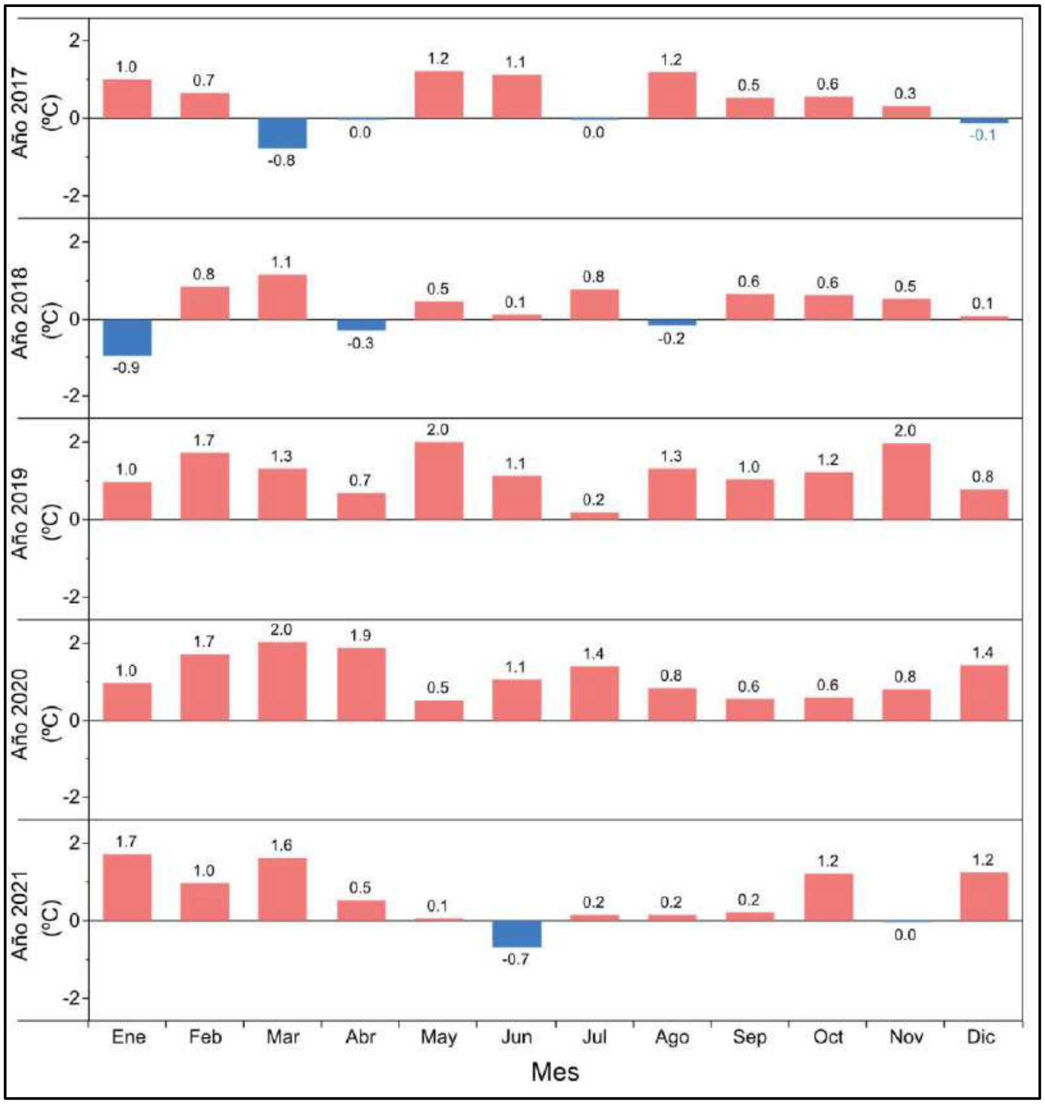

Figure 4.8. Monthly ambient temperature anomalies for the years 2017 to 2021 with respect to the average values for the base period 1990-2021. (Own elaboration with data from: Dirección de Monitoreo Atmosférico, www.aire.cdmx.gob.mx, accessed on September 10, 2022).

Figure 4.9 presents the average spatial variation of the temperature of the urban surface (not to be confused with temperature at ambient or canopy level) during March and May, obtained from the Landsat 8 satellite. The map shows the surface temperature contrasts that exist between the different land uses in the region.

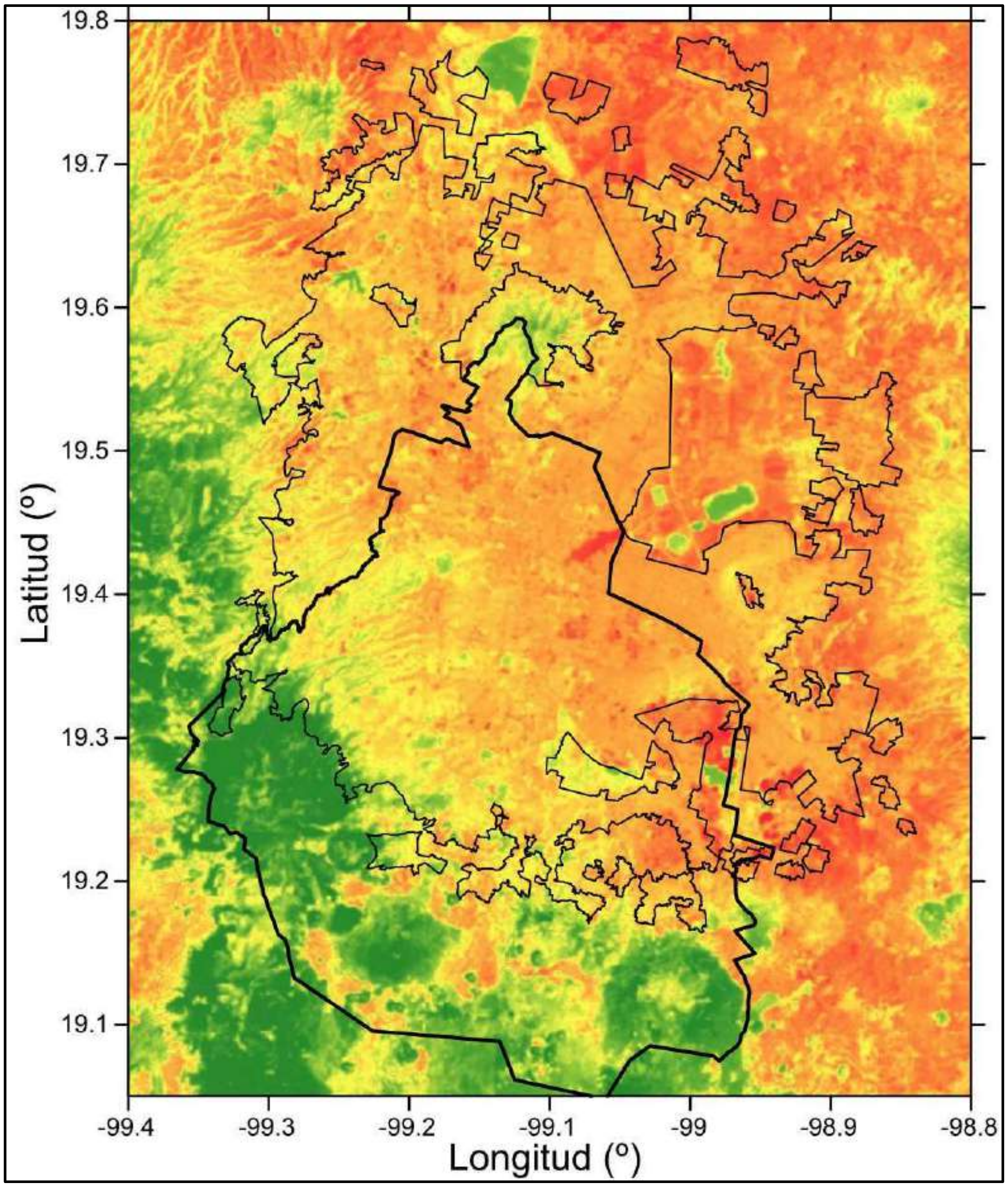

Figure 4.9. Average temperature of the land surface in the MCMA for the months of the dry-hot season (March-May), for the period 2010-2022. Higher temperatures are shown in shades of red, while lower temperatures are shown in shades of green. (Data source: collection 2 level 2 of the Landsat 8 satellite, https://www.usgs.gov/landsat-missions/landsat-collection-2-surface-temperature, accessed on November 6, 2022).

Despite the significant change in temperature in Mexico City and the pioneering work of Jauregui (Jauregui, 1997), currently the study of urban climatology is scarce. The Local Climate Action Strategy 2021-2050 (*Estrategia Local de Acción Climática 2021-2050*) of Mexico City (SEDEMA, 2021a) estimated the intensity of the city's ambient urban heat island (UHI) at 4ºC. On the other hand, the intensity of the surface UHI estimated from the approximation proposed by Chakraborty & Lee (2019) for 2020 was 0.25ºC during the day and 1.95ºC at night. Table 4.2 shows estimates of the intensity of the urban heat island in several cities of the Megalopolis as an example of the presence of surface UHI in most of the urban areas. However, this type of estimates based on modeling, as well as other derived from global satellite data, should be taken with caution. In arid regions especially, there can be a large difference between land surface (skin) UHI and canopy (air) temperatures UHI. It is necessary to perform field measurements to investigate the changes in urban climate, their relations with urban morphology and metabolism, and the potential effects on health, micrometeorology, and air quality.

Table 4.2. Average values of the intensity of the surface urban heat island for different urban clusters of the Megalopolis in 2020 based on information from the Global Surface UHI Explorer (Chakraborty & Lee, 2019).

City	Surface urban heat island, diurnal average (ºC)	Surface urban heat island, nocturnal average (ºC)
Zona Metropolitana de la Ciudad de México	0.25	1.95
Zona Metropolitana del Valle de Toluca, Estado de México	0.38	0.93
Cuernavaca, Morelos	0.29	0.58
Cuautla, Morelos	0.59	0.96
Zona Metropolitana de Puebla, Puebla	0.62	1.58
Tlaxcala, Tlaxcala	1.26	0.47
Tulancingo, Hidalgo	1.48	0.87
Pachuca, Hidalgo	-0.56	1.46
Zona Metropolitana de Querétaro, Querétaro	0.67	1.24

In the MCMA, Cui & de Foy (2012) studied the effects of vegetation cover on UHI and distinguished between skin-temperature UHI and air-temperature UHI. They found that skin-temperature heat islands within the urban canopy could reach maximum values up to 10.5ºC and had strong seasonal signal of UHI with low or negative values (cool island) during the daytime in the dry season. The air-temperature UHI was lower at night and nearly zero during the day. Also, they found correlations between the daytime land surface UHI and the difference in vegetation fraction in the urban and surrounding areas, at night the UHI correlated with atmospheric stability and weakly with differences in vegetation cover and daytime insolation. A few recent studies had addressed the urban temperature changes in MCMA (Vargas & Magaña, 2020; Mendez-Astudillo et al., 2022), Toluca (Rivera et al., 2017) and Queretaro (Mendez-Astudillo et al., 2022), using available surface and satellite data; however, the evidence is far from explaining the current situation.

Currently, the possible effects of climate change have received considerable attention from the different entities of the Megalopolis as demonstrated in the presentations and discussions at the April 2022 Virtual Workshop (see Appendix). Mexico City estimates an increase in its average temperature of between 3 and 5ºC before 2050. In the case of Puebla, projections for this century estimate an increase of more than 3ºC for the entire entity. While a decrease of around 9% in precipitations is expected in the medium term (2045-2069) (Manrique-Guevara, 2022).

Although an increase in temperature is possible in the central region of the country because of climate change, little is known about the effects it will have on the meteorology of the synoptic, regional, and local scales (SEDEMA, 2021b). Some of the formation processes of secondary compounds (for example, the formation of O_3) are sensitive to climate, therefore, the impacts of climate change are expected to also involve the way pollutants are transformed, dispersed, and deposited (Fiore et al., 2015; Jacobs & Winner, 2009; Fu & Tian, 2019). Changes in temperature, rainfall patterns and droughts can increase the concentration of $PM_{2.5}$ due to the increase in the frequency and intensity of fires, the emission of soil compounds, the increase in emissions of organic compounds of biogenic origin and by the expansion of eroded soil.

The increases in the concentrations of some pollutants (such as O_3) induced exclusively by climate change are known as climate change penalty. This penalty has important implications for air quality management and its quantification involving complex meteorological, chemical, and biological processes and feedbacks that are not yet well-understood (Fiore et al., 2015). The climate penalty will occur even in the absence of changes in anthropogenic emissions. To date, the climate penalty for the cities of the Megalopolis is not known with precision, however, it is assumed that with the increase in temperature, the levels of air pollution could increase. In the case of Mexico City, the MCMA's ProAire 2021-2030 evaluated that the climate penalty could be between 2 and 12 ppb for O_3, based on estimates made by different authors for other regions (for example., Wu et al., 2008; Gonzalez-Abraham et al., 2015; Kelly et al., 2012). The document highlighted that the climate penalty could outweigh any benefit that could be obtained from the program's actions to decrease O_3 concentration. Estimating the climate penalty for $PM_{2.5}$ is difficult to obtain from the available evidence, therefore its impact is unknown. On the other hand, there are other harmful compounds that are also susceptible to climate change such as mercury, persistent organic compounds and some allergens.

4.4.2. Influence of planetary boundary layer on air quality

The problem of pollution has generally been studied from surface observations, both of air quality and meteorology; however, the processes that occur in upper regions of the atmosphere (for example, the planetary boundary layer) and on larger spatial scales have effects that have begun to be studied from new measurements in the MCMA.

The planetary boundary layer (PBL, also known as atmospheric boundary layer) is the bottom layer of the troposphere that is in contact with the surface of the earth. The height and thermodynamic structure of the planetary boundary layer have an important influence on air quality since they modulate the vertical and horizontal transport of air pollutants. The PBL height is variable in time and space, ranging from tens of meters in statically stable situations, to several kilometers under convective conditions. The PBL has a marked diurnal cycle over land. During daytime, the PBL consists of a mixed layer (or convective boundary layer), which is stirred by solar heating of the surface and convection of warm moist air, thus mixing the air within the boundary layer. During nighttime, turbulence decays, the air that was mixed during the day remains above the much lower nighttime stable boundary layer known as the residual layer. Cumulus and stratocumulus clouds can form within the top portion of a humid PBL, while fog can form at the bottom of a stable boundary layer.

In Mexico City, the complex topography, the variability of daytime insolation, the regional climate and the urban heat determine the evolution, structure, and height of the PBL. Burgos-Cuevas et al. (2021) analyzed 28 years (1990–2017) of daily data from radiosondes of the National Meteorological Service (SMN, *Servicio Meteorológico Nacional*) to evaluate the vertical stability of the PBL and the stratification characteristics related to air quality. Their results identified the recurring presence of thermal inversions from October to April, more frequently in winter, when a greater stratification was also observed. The results showed that the surface concentration of pollutants (such as PM and CO) was higher when there were multiple thermally-stable layers, compared to days in which there was only one thermally-stable layer. This study illustrates the complexity of the PBL over Mexico City and the influence of its stratification on air quality.

Since SMN launches radiosondes only one to three times a day, it does not provide enough temporal resolution to elucidate the diurnal cycle and processes in the PBL. Recently, remote sensing has been employed to study the vertical structure of the atmosphere of Mexico City. García-Franco et al. (2018) analyzed the backscatter data of light pulses emitted by a LIDAR (acronym for Light Detection and Ranging) system from measurements carried out during a continuous period between 2011 and 2016 in the southern part of Mexico City. They found a seasonal variation in the maximum height of the mixed layer and its growth rate. The average diurnal evolution of the mixed layer height showed a maximum average value of 2750 m above ground level (magl) around 16:00 and a minimum average value of 850 magl around 07:00, with minimum below 500 meters during the winter months. The maximum heights of the mixed layer occurred during the warmest months (March and April), with values greater than 3000 magl, while the lowest heights were observed in the coldest months (September to December), with values less than 2700 magl. They also observed an increasing trend in the minimum values that they attributed to urban warming, as well as a clear anti-correlation between high-pollution episodes and the height of the mixed layer.

Osibanjo et al. (2022) conducted an intercomparison of microwave radiometer, micro-pulse lidar and radiosondes over three-month period and found an overall good agreement in the detection of the convective and residual boundary layer heights, but lower agreement for the stable boundary layer height due to the difficulty associated with the instruments to make measurements below 120 magl (see Figure 4.10). The values of the convective layer height were slightly lower (~1755 and 2332 magl) than those reported by García-Franco et al. (2018). They observed that the highest elevations in the convective and residual layers occurred on days with clear skies and higher surface temperatures, while the lowest elevations occurred on predominantly cloudy days. Burgos-Cuevas et al. (2022) compared the estimated PBL heights obtained from a ceilometer and a Doppler lidar and found that the maximum height of the PBL estimated with the backscattering of the ceilometer was greater than the estimated height by thresholding the Doppler lidar data. They deduced that the mixing mechanisms in the PBL are not restricted to diurnal convection and are also influenced by other factors, such as thermally driven winds.

The above studies illustrate the importance of using different remote-sensing retrievals to better understand and parametrize the PBL in a very complex orographic situation such as Mexico City.

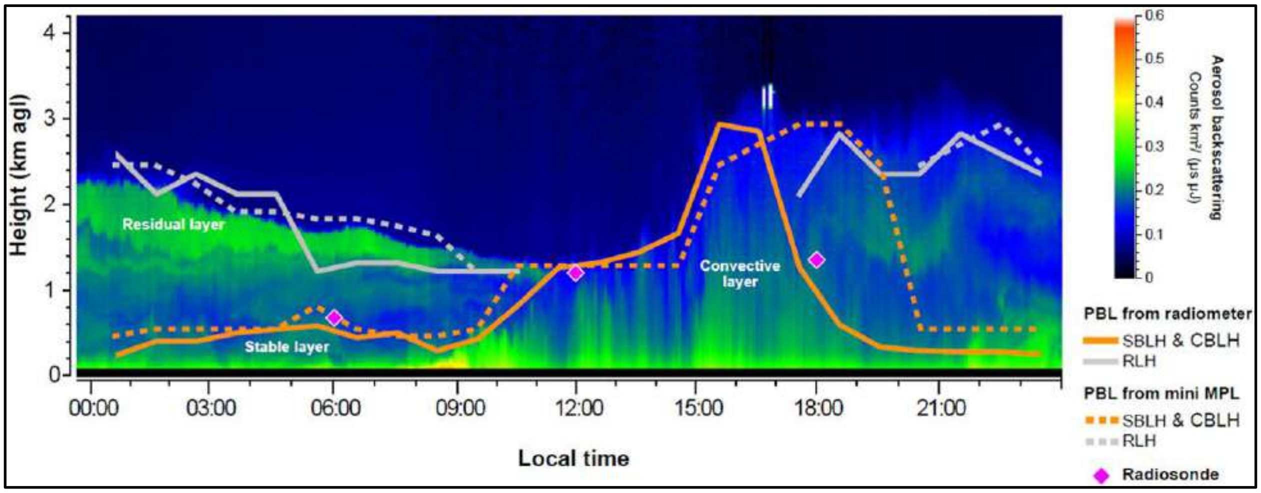

Figure 4.10. Example of the evolution of the planetary boundary layer observed by different instruments: radiometer (solid lines), LIDAR (dotted lines) and radiosondes (fuchsia diamonds). The background image corresponds to the aerosol vertical distribution obtained from the backscattering of the light emitted by the LIDAR. (Source: Osibanjo et al., 2022).

Using continuous data from a microwave radiometer and air quality observations, Osibanjo et al. (2021) analyzed the effects of the evolution of the boundary layer on air pollution during the severe O_3 pollution episode of March 2016 (March 12-15) in Mexico City. The first few days prior to the smog episode (March 8-11) were affected by the passage of a deep upper tropospheric trough (Barret et al., 2019), accompanied by a strong advection that kept significant ventilation over the basin for several days. Shortly before the smog episode (March 10), the maximum height of the convective layer was maintained at ~2.5 km above ground level; but then decreased to ~1.2-1.7 km for days with the most severe pollution . During the first few days, the strong advection allowed O_3 precursors to be quickly flushed out from the basin; after March 11, the winds weakened rapidly and a strong temperature inversion near the surface during the night allowed a rapid accumulation of pollutants. During the day of March 12, the height of the convective layer barely reached 1.2 km, well below the height of the mountains surrounding the basin, confining the pollution within the basin. In the following days, the height of the daytime convective layer gradually increased; however, the stagnant condition was maintained for the following days, causing high daytime O_3 levels. The intense photochemical activity, in the presence of high levels of precursors, caused the O_3 concentration to reach ~200 ppb on March 14. The episode ended after March 17, when the boundary layer recovered its usual behavior, allowing for greater dilution, and horizontal advection contributed to the gradual removal of pollutants. This study shows that the diurnal evolution of the PBL is crucial to air quality studies as it affects the exchange and distribution of pollutants near the surface.

As mentioned above, local meteorological conditions play an essential role in the occurrence of poor air quality episodes, as meteorology affects the formation, transport, and dispersion of pollutants. The Meteorology and Solar Radiation Network (*Red de Meteorología y Radiación Solar*), which is part of SIMAT, maintains a permanent monitoring of the meteorology at the ambient and vertical level, making it possible to investigate the influence of local meteorology on air pollution (see Section 2.1.4 in Chapter 2). The work carried out by de Foy et al. (2005, 2006a, 2006b, 2008) during the MCMA-2003 and MILAGRO 2006, and some recent studies (for example, Salcido et al., 2019; Silva-Quiroz et al., 2019) highlighted the importance of synoptic scale meteorology in air pollution in the MCMA, although these studies analyzed only a few events.

Recently, Díaz-Esteban et al. (2022) examined the weather patterns that produce circulation characteristics that result in poor air quality in the Mexico basin during the dry season (November-May) using cluster analysis of the 500-hPa winds over a 30-year period (1990-2019). They observed above-normal pollution levels occurring under the influence of mid-tropospheric high-pressure systems centered around 20°N moving eastward over Mexico. The high pollution events associated with this pattern generally occurred during the dry season: March to May for O_3 and December to February for NO_2 and $PM_{2.5}$. On an interannual scale, they identified an association between El Niño–Southern Oscillation (ENSO) and the frequency of weather patterns related to pollution, where La Niña years favored the occurrence of patterns associated with more pollution, while El Niño years with less pollution. The seasonality and predictability of pollution-related atmospheric patterns in the Mexico basin will be useful for air quality assessments at both seasonal and intra-seasonal scales.

4.4.3. Air pollution and surface ultraviolet radiation

The impacts of medium- and long-term changes in incident solar radiation over the Mexico Basin have been studied relatively little. Pollutants present in the atmosphere interact with solar radiation, absorbing or dispersing it, reducing the intensity that reaches the surface. Because most pollutants are concentrated within the PBL, radiation attenuation due to air pollution was strongest near the surface. In a recent work, Ipiña et al. (2021) analyzed 20 years of measurements of the Ultraviolet (UV) Index and air quality carried out by SIMAT in the MCMA. They identified an increasing trend in the intensity of solar UV radiation incident on the surface, with a slope of 0.9% per year (see Figure 4.11). The estimated reduction in radiation was ~40% for the year 2000 and ~20% in 2019. Aerosols made the largest single contribution to radiation decrease, however, gases contributed more than half of the total reduction. The reduction in the concentration of air pollutants increased the intensity of the radiation reaching the surface. With the decrease in pollution levels achieved by effective air quality management policies in the last two decades, an increase in solar UV radiation has been favored with collateral impacts on air quality by increasing the photolysis rates in the atmosphere, intensifying the production of secondary pollutants (namely, O_3 and secondary aerosols), and increasing the risks to human health (for example, cataracts, skin cancer) due to greater exposure to UV radiation.

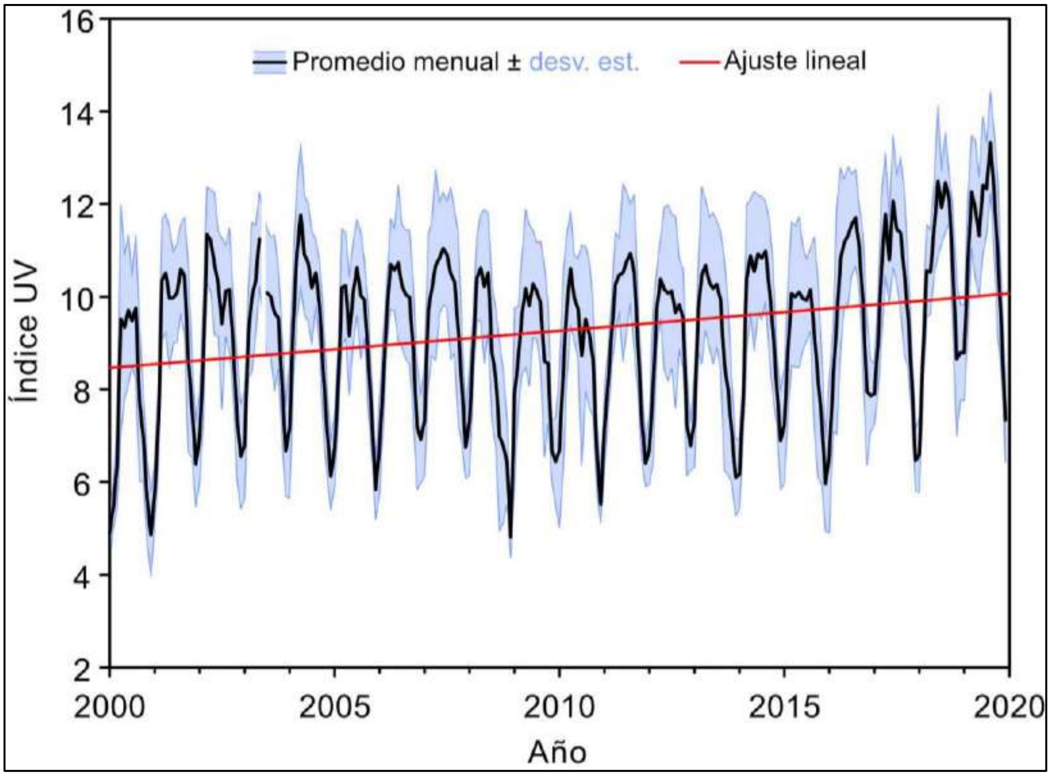

Figure 4.11. Time series of the monthly averages of the UV Index (black line), its standard deviation (blue shading) and linear adjustment (red line) in the period 2000-2019, for Mexico City. (Source: Adapted from Ipiña et al., 2021).

The possible effects of radiation on the formation of O_3 is a relevant aspect that air quality management must consider. ProAire 2021-2030 focuses on the reduction of aerosols, however, its compliance could induce an increase in incident solar UV radiation and photochemical activity with possible increase in O_3 concentrations, compromising the reduction goals for this gaseous pollutant.

4.5. Short-lived climate forcers

It has been demonstrated that the reduction of a few species known as short-lived climate forcers (SLCFs)[2] may slow the rate of near-term climate change from regional to hemispheric scales, in addition to significant benefits for energy efficiency, human health, crop production, and ecosystems (UNEP-WMO, 2011). The major SLCFs with lifetimes under a few decades are black carbon (BC, ~ days to weeks), methane (CH_4, ~ a decade), tropospheric O_3 (weeks to months) and some hydrofluorocarbons (HFCs, average 15 years). Due to their nature, these substances can be rapidly controlled and reduced with existing technology (UNEP-WMO, 2011; UNEP, 2011a, 2011b; UNEP-CCAC, 2018), providing near-term climate benefits and improving air quality. It is

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[2] Short-lived climate forcers (SLCF) are also known as short-lived climate pollutants (SLCP).

important to emphasize that despite these short-term benefits, reducing long-term warming will also require measures to reduce current and future CO_2 emissions.

Black carbon is a major component of soot; it is produced from the incomplete combustion of fossil fuels, biofuels, and biomass. Anthropogenic CH_4 is emitted to the atmosphere from ruminant livestock, rice cultivation, microbial waste processing (landfills, manure, and wastewater), coal mining, and oil and natural gas systems; it has about 34 times the Global Warming Potential (GWP) of CO_2 (100-year horizon). Due to its shorter lifetime, it is even more effective over the 20-year time horizon. As discussed above, tropospheric O_3 is not directly emitted; it is a secondary pollutant that is formed by atmospheric photochemical processes and must be controlled by reducing its precursor pollutants, primarily NO_x, CO, and VOCs, as well as CH_4. Ozone is harmful to human health and agriculture; it is also a powerful greenhouse gas.

Many countries have included or in the process of including BC reduction in their national determined contributions (NDC) to the United Nations Framework Convention for Climate Change (UNFCCC, https://unfccc.int/). Mexico was the first country to commit to reducing BC as part of its commitment to the UNFCCC Conference of the Parties (COP21) held in Paris in December 2015. During the COP 26 in Glasgow, Scotland, in November 2021, Mexico joined over 100 countries in pledging to reduce CH_4 emissions by 30% by 2030 (UNEP, 2021).

There is a high degree of uncertainty in estimating global CH_4 emissions, in large part due to the availability and quality of data. The most recent estimate from IEA (2023) suggests that annual global CH_4 emissions are around 580 million tonnes (Mt),[3] of which 355 Mt (about 60% of the total) are generated from anthropogenic sources. Agriculture (enteric fermentation, manure management, rice cultivation, and others), energy sector (oil, natural gas, coal, biofuel), waste, and other sources contribute 39.9%, 37.5%, 19.8%, and 2.7%, respectively, of anthropogenic CH_4 emissions. As noted in the report from IEA (2023), there is a large difference between data based on measurement campaigns and scientific studies, and the emissions reported by official public agencies. In fact, the total global CH_4 emission reported to the UNFCCC was about 30% lower than the IEA estimates in 2022; the largest discrepancy was in the energy sector. Most countries and regions still have little or no measurement-based data and the data reported are of poor quality, highlighting the challenges of assessing and mitigating CH_4 emissions.

As mentioned in Chapter 3, INECC is responsible for preparing the National Inventory of Greenhouse Gas Emissions and Compounds (INEGYCEI) (INECC, 2021). The most recent version of the INEGYCEI includes estimates of emissions of CO_2, CH_4, nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and BC for the period 1990 to 2019 (INECC, 2021). Most of the official greenhouse gas (GHG) inventories reported by SEMARNAT and INECC, up to now, have been prepared using the IPCC Tier 1 approach (IPCC, 2006), which is the simplest, including the Sixth National Communication (SEMARNAT-INECC, 2018).

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[3] Converting CH_4 emissions to equivalent amount of carbon dioxide (CO_2e) will depend on the GWP of CH_4 used in the calculation. For example, INECC uses GWP of 28, therefore 580 Mt CH_4 = 16,240 Mt CO_2e (INECC, 2021).

As in the case of the other countries, there is a discrepancy in the reported CH_4 emission from Mexico to UNFCCC and the IEA estimates. The total CH_4 emissions reported for 2019 is 6,270 Gg[4] (INECC, 2021), while the EIA estimated an emission of 6,051 Gg (EIA, 2023). However, although the difference in the total amount is small, there is a large difference in the contributions originating from the different sectors; for example, for the energy sector, the INECC reported CH_4 emissions that were 50% lower than the IEA estimates; on the other hand, about 35% higher for the agriculture sector. Similarly, Shen et al. (2021) also reported that the official Mexican CH_4 inventories for the oil/gas sector are underestimated based on observations made by these authors using satellite images.

Mexico has been making several efforts to assess SLCFs emissions and to foster mitigation measures. These efforts started in 2010, with the study entitled "Emerging topics in climate change: methane and BC, possible co-benefits and development of research plans" (INE-MCE2-UNAM, 2011). This study was followed by a series of technical workshops and ministerial meetings, which gave rise to the first-order SLCF national planning for Mexico under the Climate and Clean Air Coalition (CCAC) SNAP (Supporting national planning for action on Short-Lived Climate Pollutants) initiative in 2013 (MCE2-INECC, 2013). This process led to the development of a research initiative by MCE2 to better characterize the emission sources of SLCFs in the country, including multiple wastewater treatment plants, landfills, research livestock farms, brick kilns, residential cookstoves, on-road and non-road fleets of heavy-duty diesel vehicles. This initiative resulted in the publications of more than twenty peer-reviewed articles. The following describes the results from some of the measurements conducted specifically in the MCMA and the Megalopolis region.

4.5.1. Black carbon emissions from on-road and off-road diesel vehicles

Emissions of BC, organic carbon, and other inorganic components of $PM_{2.5}$, as well as CO, NO_x, SO_2, ethane, acetylene, benzene, toluene, and C2-benzenes were obtained under real-world driving conditions of 20 diesel-powered vehicles encompassing model years 1998 to 2011, and EPA98, EPA03, EPA04, EURO3-5 emission level technologies in Mexico City with the chasing technique using the Aerodyne Mobile Laboratory (AML) (Zavala et al., 2017a). The results showed higher PM emissions factors for urban buses with older technologies than for the other vehicle types, and a marked dependency on vehicle emission control technology, demonstrating the benefits of tighter Tier regulations and independent testing to verify the efficacy of reduced emissions standards for diesel vehicles. A comparison of the results with the US-EPA MOVES-2014b model showed that the model underestimates CO, OC, and selected VOC species, whereas there is better agreement for NO_x and BC. Observed OC/BC ratios were larger compared to ratios measured in California using similar technique, further demonstrating the need for using locally-obtained emission factors database in developing countries to reduce the uncertainty in the emissions estimates and to improve the evaluation of the effectiveness of emissions reduction measures.

Emission factors for gases (CO, CO_2, and NO_X) and PM (BC component and total PM) for a variety of off-road diesel vehicles in Mexico were obtained using Portable Emissions Measurement Systems (PEMS) technique in high temporal resolution. The vehicles sampled included backhoes, bulldozers, large wheel loaders, excavator, crane, tractor, air compressor and

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[4] Gg = Gigagram; 1 Gg=1000 tonnes = 1 Kt

electric generator used in the construction and agricultural activities. For a selected number of these vehicles, the emissions were further characterized with wall-flow diesel particulate filters (DPFs) and partial-flow DPFs (p-DPFs) installed. To the best of our knowledge, this was the first study of emissions characteristics for off-road vehicles in Mexico and the results contributed to the understanding of emissions from off-road vehicles under real-world operating conditions. Tests conducted in a selected number of sampled vehicles indicated that the reductions for BC emission factors were significantly large (>99%) when DPFs were installed and the vehicles were idling, and the reductions were moderate (in the 20-60% range) when p-DPFs were installed, and the vehicles were in operating conditions. Given the potentially large emission reductions, there is a strong need to further study the emission benefits of control technology for retrofitting off-road diesel-powered vehicles in Mexico (Zavala et al., 2017b).

4.5.2. Methane emissions from wastewater treatment plants

In Mexico, the management of industrial and municipal wastewater emits approximately 13% of the anthropogenic CH_4, an amount to which indirect CO_2 emissions must be added that correspond to the consumption of electrical energy necessary for its operation. Therefore, the contribution to the national GHG inventory of this activity is significant. On the other hand, there is very little information on direct measurements for the calculation of GHG emissions in sewage and wastewater treatment plants (PTAR) in Mexico (Noyola, 2022).

The IPCC guidelines are usually used for estimating CH_4 emissions from wastewater treatment plants (WWTP) (IPCC, 2006). However, they do not consider emissions due to dissolved CH_4 in the incoming wastewater, nor emissions that occur during the biological nutrient removal. Both are common operations in well managed treatment facilities.

In such a context, Paredes et al. (2015) investigated the emission factors of CH_4 in five stabilization ponds, covering representative plant capacity, geographical distribution, and the variability of the environmental conditions of each region in Mexico. Based on the analysis of the measurements results, a value of 0.43 kg CH_4 kg^{-1} BOD removed (0.32-0.58) was suggested as a representative value for well-operated municipal stabilization pond system in Mexico. BOD (biochemical oxygen demand) represents the amount of oxygen needed to break down organic matter in water.

There is no WWTP free of CH_4 emissions since sewage is an exogenous source of this gas. Furthermore, the removal of nutrients (nitrogen) will also produce N_2O in the anaerobic (or anoxic) stage. To account for these emissions, Noyola et al. (2018) proposed a methane correction factor (MCF) of 0.06 for a well-operated centralized aerobic WWTP, for intertropical regions. Additionally, they suggested to calculate the methane emissions of the aerobic WWTP + anaerobic digester arrangement as an integrated process, with an MCF of 0.32. The modifications were supported by *in situ* assessment of fugitive CH_4 emissions in two facilities in Mexico (Cerro de la Estrella in Mexico City and Dulces Nombres in Monterrey) and relevant literature data.

Based on the contributions of Paredes et al. (2015) and Noyola et al. (2018), it was possible to apply Tier 2 in aerobic WWTPs in Mexico (responsible for 55 to 70% of the treated flow in Mexico) and lagoon systems (10% of the treated flow). Thus, Tier 2 would apply to emissions from 65 to 80% of the wastewater treated in Mexico.

A new study conducted in several WWTPs in Mexico indicated that CH_4 emissions from two sources within the treatment process (primary sedimentation and aeration tank) were of equal importance (Noyola, 2022). An effective mitigation measure was to avoid the generation of CH_4 in the sedimentation units, through an adequate sludge purge frequency. The results showed that, in almost all the plants visited, the concentration of dissolved CH_4 tripled on average in the primary sedimentation in relation to the content of the influent. Indirect emissions (associated with electricity consumption) exceeded the values of direct emissions by a wide margin, so reducing indirect emissions would be a priority for a strategy to reduce emissions in WWTPs. Indirect emissions, due to electricity consumption, represented more than 60% of the total emissions in the scenarios considered, with practically equal parts (around 20% each) of emissions in the WWTPs and from the sludge discharged into the sewer system.

It should be noted that IPCC updated the Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). However, the methodology updated in 2019 for Tier 1 recommends a value of 0.03 for the MCF without distinguishing well-operated plants from poorly operated ones.

4.5.3. Methane emissions from livestock enteric fermentation

Globally, agriculture sources were estimated to contribute about 40% of total anthropogenic CH_4 emissions. Enteric fermentation, manure management, rice cultivation, and others account for 64%, 7%, 17%, and 12%, respectively of these emissions (GMI, s.f.). In the case of Mexico, agriculture is the largest source of CH_4 emissions; livestock emitted more than 80% of CH_4 emissions from the agricultural sector considering enteric fermentation and manure management (Castelán-Ortega, 2022; INECC 2021).

Castelán-Ortega et al. (2019) reported the Tier 2 level inventory of CH_4 emissions of 2,039±205 Gg year^{-1} from bovine enteric fermentation (Figure 4.12). This was the first Tier 2 level inventory developed in Mexico using locally determined emission factors for the country's different geo-climatic systems using the open-circuit respiration chamber technique. Activity data obtained through a national survey and an extensive collection of bibliography published in scientific articles (mainly) and other sources such as conference proceedings, books and theses were used. This information included data on feeding systems, since feed consumption is the main factor that determines CH_4 emissions in cattle, types and breeds of cattle, production levels, production orientation (milk, meat, dual purpose), ages and weights of animals, among others. It is important to highlight that Castelán-Ortega & Ku-Vera (2019) had *in vivo* emission factors for enteric CH_4 for all the geo-climatic regions of Mexico, therefore it was possible to estimate the enteric CH_4 emissions by state, category, age, weight, and productive function of all the states of the Mexican Republic.

The results of this national inventory showed that most of the CH_4 emissions were recorded in the dry climate region, followed by the dry tropical climate region, that is, in the northern states of the republic for the first case, and in the coastal plain states of both the Pacific Ocean and Atlantic Ocean coasts, for the second case. Regarding the Megalopolis region, it was estimated that the states that made up this area emitted ~131 Gg of CH_4 year^{-1}, which was 6% of the national inventory of enteric CH_4 emissions (Castelán-Ortega & Ku-Vera 2019).

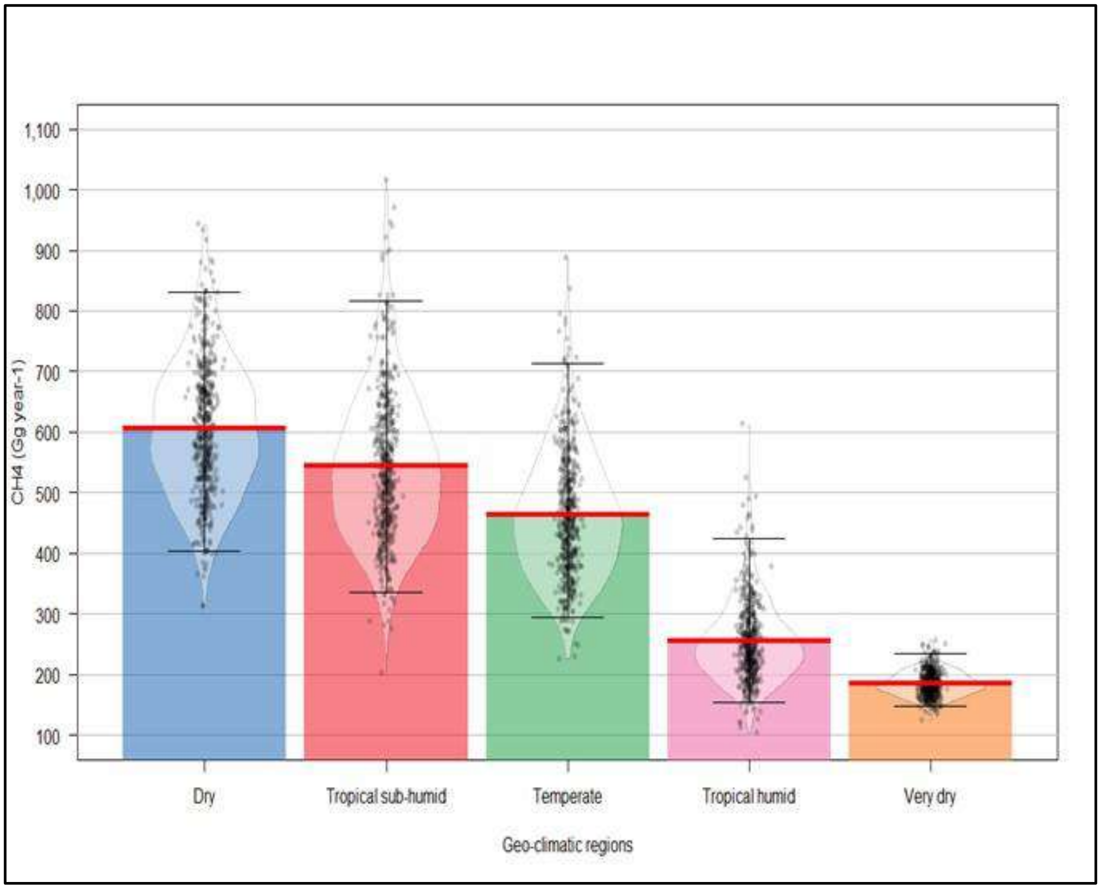

Figure 4.12. Tier 2 inventory of CH_4 emissions from enteric fermentation by geo-climatic region of Mexico. (Source: Castelán-Ortega and Ku-Vera, 2019.)

Castelán-Ortega and his team have also investigated different mitigation strategies for enteric CH_4 by using different feeding strategies and additives in the cattle diet. They have identified at least three natural additives (*Cosmos bipinnatus*, *Cymbopogon citratus*, tropical legume *Samanea saman*) that have been shown to reduce the production of CH_4 (Hernández-Pineda et al., 2018; Vázquez-Carrillo et al., 2020; Valencia-Salazar et al., 2018, Vázquez-Carrillo et al. 2023).

4.6. Air Quality Modeling and Forecasting in the Megalopolis

Air quality modeling is a numerical simulation of the transformation and dispersion of air pollutants in the atmosphere, and how they affect air quality. The models are useful to quantify the relationship between emissions, depositions (wet and dry), meteorology and concentrations, as well as to analyze past and future scenarios, and the effectiveness of emission mitigation strategies. This makes air quality modeling an essential research tool in designing and evaluating public policies based on emission control strategies, and it is a basic tool in air quality management. In forecast mode, air quality models are also needed for forecasting purposes, and therefore to alert the public in advance of potential air pollution episodes, as well as implement control actions before they occur (see for example, Baklanov and Zhang, 2020).

The use of models is necessary for the design and evaluation of air quality management strategies; however, it is important to recognize that model results may contain substantial errors because of incorrect or inadequate meteorological and air quality input data, as well as inherent uncertainty due to the stochastic nature of the turbulent atmospheric motion that is responsible for the transport and transformation of pollutants (Fox, 1982). Modelers should quantify the uncertainties, for example, by validating the model results with data from observations. Furthermore, it is important to communicate the uncertainties to the decision makers and to emphasize the challenge of making decision with quantified uncertainty.

In Mexico, the main air quality modeling efforts have been carried out in the MCMA. The use of meteorological models in combination with transport models goes back to the 1990s during the MARI project (The Mexico City Air Quality Research Initiative) (LANL and IMP, 1994). During the IMADA-AVER (Investigation on Particulate Matter and Atmospheric Deterioration-Aerosol and Visibility Research) campaign, Fast and Zhong (1998) used surface and high-altitude meteorological data to assess atmospheric dynamics during various O_3 pollution events. Young et al. (1997) modeled photochemical O_3 production using a multilevel box model. However, it was not until the field campaigns based on observation and numerical simulations from models carried out as part of the MCMA-2003 and MILAGRO 2006 projects (Molina et al., 2007, 2010) that large volumes of information were obtained to improve understanding of the chemistry, dispersion and transport processes of pollutants emitted into the atmosphere in the MCMA (for example, de Foy et al., 2005, 2008; Zhang et al., 2009. Song et al., 2010; Dzepina et al., 2011).

Since 2000, SEDEMA has used MCCM model (Multiscale Climate Chemistry Model) for the design and evaluation of management measures. In 2017, with the collaboration of Barcelona Supercomputing Center, Mexico City government has developed an air quality forecasting system (AQFS-CDMX) to alert the public of high pollution event 24 hours in advance. The forecasting system consists of WRF-ARW (Weather Research and Forecasting - Advanced Research) meteorological model, the CMAQ (Community Multi-scale Air Quality) chemical transport model, and HERMES-Mex (High-Elective Resolution Modeling Emission System for Mexico) for the disaggregation of emissions (SEDEMA, 2017; Guevara et al., 2017). The forecast model used atmospheric scientific information obtained from MCMA-2003 and MILAGRO-2006 field campaigns and recent improvements in the emission inventories carried out by Mexico City Secretariat of Environment (SEDEMA). The model performance is relatively good for O_3; however, the uncertainty of the model increases as ozone concentration increases above 100 ppb during high pollution events that usually trigger atmospheric contingencies in the MCMA. The performance for $PM_{2.5}$ forecast is not as good, it has difficulty reproducing diurnal variability and tends to underestimate concentrations.

Recently, AQFS-CDMX was used intensively in the evaluation of actions for different management scenarios during the preparation of ProAire ZMVM 2021-2030 (SEDEMA et al. 2021). SEDEMA maintains a continuous effort to guarantee the operation of the system and improve forecast performance. It is important to improve inventories of the region with higher resolution and updated knowledge of the atmospheric chemistry of the MCMA and include all emission sources.

Outside of Mexico City, there are no operational developments of similar modeling activities in the rest of the entities of the Megalopolis. The major barriers are the availability of air quality monitoring data of acceptable quality, the development of a robust emissions inventory and a model-ready emission input in the Megalopolis, qualified technical personnel, and the need to increase computing and data storage infrastructure.

There are forecasting efforts carried out by academic institution; for example, the ICAyCC-UNAM has a 72-hour forecast model based on WRF-CHEM for CO, NO_X, O_3, PM_{10} and SO_2 for central Mexico, covering the cities of Toluca, Cuernavaca, Tlaxcala, Puebla and Mexico City (Rodríguez Zas & García Reynoso, 2021). The graphic outputs are available for consultation online (http://grupo-ioa.atmosfera.unam.mx/pronosticos/index.php/wrf-chem, accessed March 31, 2023). The forecast system has an acceptable performance. Modeled O_3 has a good agreement with the observations, but the agreement is poorer for $PM_{2.5}$ particles. During contingency events, concentrations are underestimated in the model. Areas for improvement include real-time emissions from fires, identify and reduce uncertainty in the national emissions inventory (INEM), update land cover parameters for the use of urbanized models to improve meteorology, increase modeling domain to consider regional sources that influence air quality.

Emission inventories provide essential input data for atmospheric chemical transport models. Therefore, uncertainties in the emission sources are an important factor in determining the simulated and predicted accuracy of the data obtained from the models, since these uncertainties can have impacts on the design of control strategies. Methods for establishing an emissions inventory include a bottom-up approach based on the identification of human activities, energy consumption statistics, and various emission factors, but can also use a top-down approach with inverse modeling that use monitoring data from satellite remote sensing and ground observations. The former approach usually has significant uncertainties in the statistical data, emission factors and spatiotemporal distribution coefficients, therefore the latter approach can complement the former by reducing these uncertainties.

For many years, the lack of a model-ready emission inventory was a major barrier for modeling efforts, not only in Mexico City, but also in the rest of the country. Constructing inventories with a structure and content that meets the requirements for use in air quality models, that is, input in the form of grid cell, hourly and chemical species-based emissions, was a challenge for the developers and users of the models. To resolve this situation, in the case of Mexico City, a thorough review of the emissions inventory was carried out, introducing a set of improvements and a system for processing emissions to produce an inventory ready for modeling with adequate spatial and temporal disaggregation. (Guevara et al., 2017). Recently, INECC used the 2014 national emissions inventory (from area, stationary and mobile sources) to prepare a model-ready emission inventory of national criteria pollutant for use in WRF-Chem. The emissions domain includes the Mexican Republic and the central zone, which included the metropolitan areas of Mexico City, Puebla, Tlaxcala, Pachuca, Tula, Toluca, and Cuernavaca (INECC, 2017).

At the Megalopolis level, it is necessary to increase the spatial, chemical, and temporal resolution of the emissions inventory and include emerging sources of pollution. It is also necessary to accelerate the continuous updating of the emissions inventory for modeling so that the information can be useful in decision making. Currently, only Mexico City has an emissions inventory with adequate resolution and maintains a continuous effort to identify and quantify new emission sources, considering the use of observations in estimating emission profiles and their temporal variability.

Models could benefit from the availability of better meteorological and air quality information outside the urban areas, as well as the availability of meteorological data at higher altitude of the atmosphere. Satellite products open an area of opportunity to increase the spatial coverage of models and improve information on boundary conditions. Regarding the availability of high-altitude meteorological data, the ICAyCC-UNAM and SEDEMA maintain continuous monitoring using profilers; however, these data are not publicly available. On the other hand, the design of air quality monitoring networks does not always consider the needs of modeling for its configuration, therefore, it is recommended that future reviews of monitoring programs should take this into consideration.

With the exception of the MCMA, the air quality modeling and forecasting efforts are still in the early development stage in the other region of the Megalopolis. The most important challenges are the shortage of technical personnel in the academic and government sectors for the development and application of modeling tools in the design and evaluation of air quality control strategies, the availability of high quality and high-resolution emission data and meteorological parameters, and lack of computing infrastructure for modeling studies. Nevertheless, it is possible to overcome some of these challenges by taking advantage of the opportunities available in the global modeling community.

The outputs of global air quality models with publicly available data have become an alternative for air quality forecasting in some urban environments (Duncan et al., 2021). The CityAQ project, which is developed between the WRI (World Resources Institute) and the NASA Global Modeling and Assimilation Office (NASA-GMAO), use the outputs of the GEOS-Chem global model to develop a local air quality forecast, pre-fitting the model data with local air quality observations using a machine learning algorithm (Keller et al., 2021). CityAQ aims to create scalable models to combine locally available air quality monitoring information with results from global models, satellite products, and other open analytics to develop custom tools for cities (https://www.wri.org/initiatives/cityaq). This development has the potential to provide local or regional forecasts to those agencies or entities with limited resources. However, it has some limitations, for example, it requires high-quality data for algorithm training, it needs continuous forecast evaluation to identify model deviations, it has difficulties in identifying microscale weather or pollution events, small or medium size cities fit within a cell of the model, therefore, the spatial variability will depend on the variability that the adjustment algorithm manages to capture during training. Currently, adjusted GEOS-Chem model outputs for $PM_{2.5}$, O_3, and NO_2 are available for the cities of Monterrey, Guadalajara, and several cities in Guanajuato. The cities in the Megalopolis could explore using this modeling and forecasting tool.

A list of recommendations for advancing the modeling efforts in the Megalopolis is provided in Section 4.8.

4.7. Impact of COVID-19 on Air Quality in the Megalopolis

4.7.1. COVID-19 Pandemic in Mexico

The discovery in late 2019 and the rapid spread of SARS-CoV-2, responsible for the coronavirus disease COVID-19, caused dramatic changes in the activities of the population around the world (WHO 2020a, 2020b). Most countries enacted strict measures to contain the spread of the disease to protect the public health, including lockdowns, quarantines, and travel restrictions, reducing global economic activity. Air pollution was found to substantially increases the risk of infection and the severity of COVID-19 symptoms. A study in the US reported an increase in COVID-19 death rates in areas with higher average levels of $PM_{2.5}$ over the long term (Wu et al., 2020). In Mexico City, Lopez-Feldman et al. (2020) found evidence that prolong exposure to $PM_{2.5}$ increases the likelihood of dying from COVID-19. These studies emphasize the importance of enforcing existing air pollution regulations during and after the COVID-19 crisis.

In Mexico, the first cases were diagnosed during the last week of February 2020. As a precaution, basic education schools suspended activities starting March 17, 2020; this action became widespread on March 24, 2020, when all academic activities were suspended, as part of Phase 2 actions to prevent the spread of the virus. On March 30, 2020, partial confinement measures were introduced for some non-essential activities, the suspension of services offered by the public administration and the cancellation of public gatherings of more than 25 people. Faced with the advance of the pandemic, the authorities decided to apply Phase 3 actions starting April 21, 2020, which implied total ban of any non-essential activity. In the MCMA the suspension was extended to non-essential industrial and commercial activities, the reduction in public transportation service, and the promotion of “stay at home” program.

An unintended consequence of the restrictions during Phases 2 and 3 was the reduction in emissions from automobiles, industry, and commercial activity, on a scale unprecedented in Mexico, offering atmospheric scientists and air quality managers a unique opportunity to study the effects on air quality of extraordinary reductions in anthropogenic activities. Considering that most long-term pollution reduction strategies and control actions during episodic pollution events are focused on reducing emissions from automobiles and industry, this unplanned experiment was of great value to estimate under real conditions the maximum impact that could be achieved with the current management scheme.

In the Megalopolis region, many activities, such as work and education, were carried out through electronic means, and others used the flexible hybrid working arrangement (face-to-face and remote through videoconferences, email, and telecommunications). The reduced motorization and other activities resulted in the reduction of the concentrations of some pollutants as recorded in the air quality monitoring stations, as described below.

Using an indicator of the mobility of people, it was possible to show the drastic reduction in mobility, but also how some entities and cities in the Megalopolis returned to the pre-pandemic level, while others remained at lower levels when some of the confinement restrictions were lifted. This is illustrated in Figure 4.13, showing the trends in modes of transport requests in 2020 and 2021 published by Apple (CAMe, 2022), compared to pre-pandemic levels of mobility.

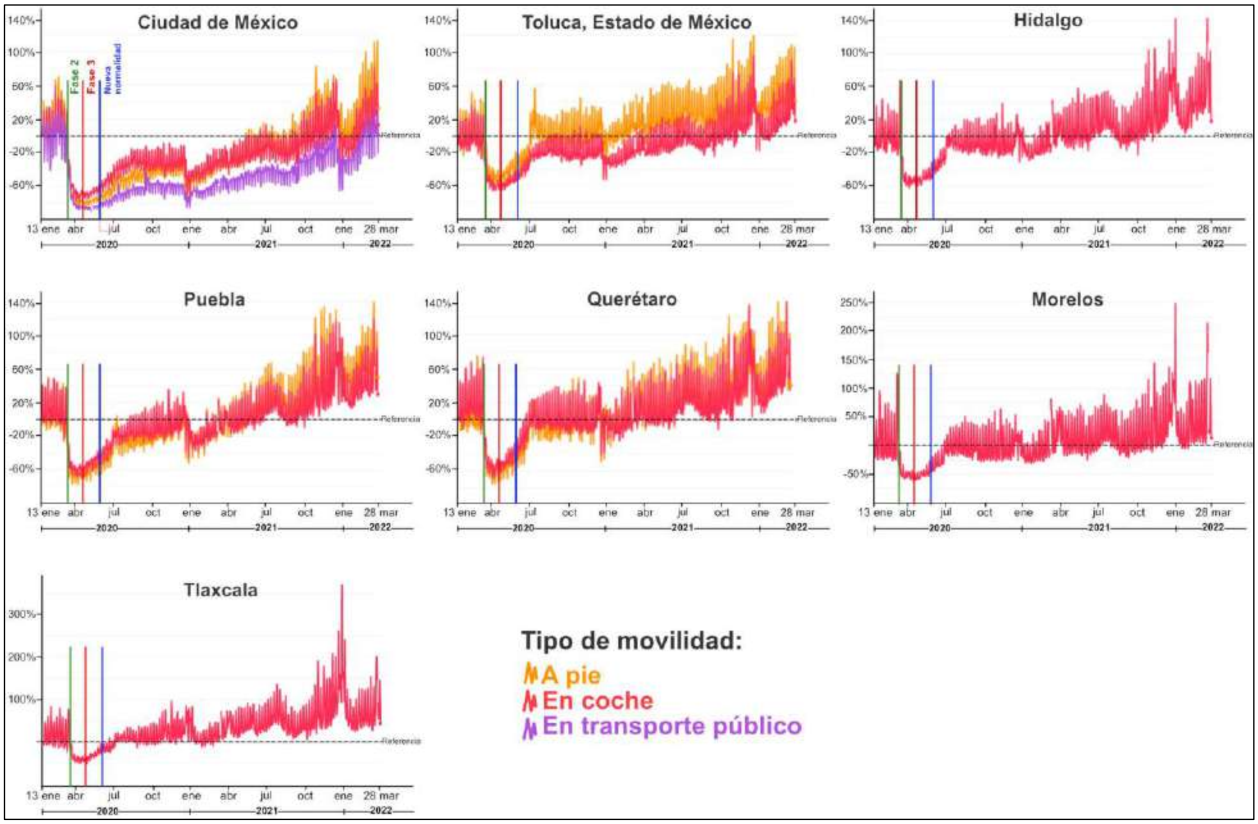

Figure 4.13. COVID-19 Mobility Trends Reports (Source: "COVID-19 - Informes de tendencias de movilidad – Apple" consultado el 16 de marzo 2022, CAMe, 2022.)

The behaviors of several entities and cities such as Hidalgo, Morelos, Querétaro, Puebla, Tlaxcala, and Toluca were like the pre-pandemic situation and only Mexico City and its metropolitan area remained with less activity. This return to the previous conditions of circulation of motor vehicles also implied the return to the emission levels that existed before the pandemic, and therefore to the previous air quality levels, modulated by other factors such as climatic and meteorological conditions, and the occurrence of forest fires.

4.7.2. Air quality in Mexico City and other regions during COVID-19 lockdown

4.7.2.1. Mexico City Metropolitan Area

During the pandemic, SIMAT maintained continuous monitoring at most of its stations. It is worth noting that the lockdown period in Mexico City coincided with the season in which the highest concentrations of secondary pollutants (O_3 and $PM_{2.5}$) are recorded, which runs from February 15 to June 15, due to the unique topography and meteorological conditions in the Mexico basin that favor the formation of secondary compounds, as described in Chapter 2. In addition, the city was under the influence of the transport of pollutants generated by forest fires in neighboring states.

SIMAT also participated in a study coordinated by WMO Global Atmospheric Watch (GAW) program to understand the behavior of key air pollutant species during the COVID-19 pandemic period, when exceptionally low emissions were observed worldwide (Sokhi et al., 2021). In this study, the information on air quality and meteorology of 63 cities in 25 countries across 7 different geographic regions of the world, including Mexico City, was analyzed. Figure 4.14 shows the observed percentage changes of key pollutant species for the lockdown periods in 2020, compared to their corresponding periods in 2015–2019 for the cities participating in this study.

As shown in Figure 4.14, in the case of Mexico City, comparison of the average concentrations of 2020 with those of 2015-2019, for the period from April 1 to June 14, showed reductions of 13, 12, 18, 37, 42 and 39 % in the concentrations of $PM_{2.5}$, PM_{10}, PMC (particles with diameters between 10 and 2.5 µm), NO_2, CO and SO_2, respectively, while O_3 showed an increase of 2% (Sokhi et al., 2021).

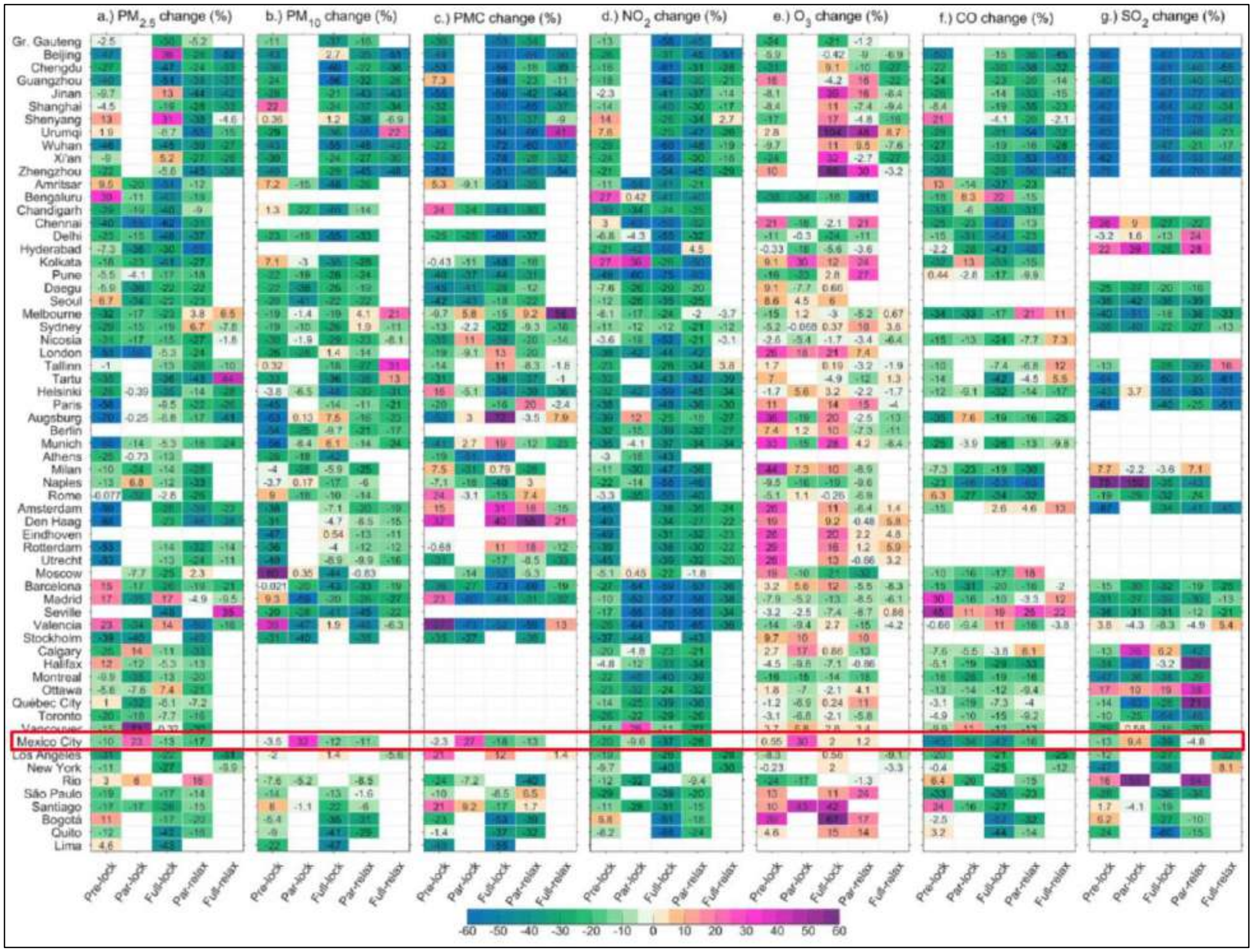

Figure 4.14. Observed percentage changes for (a) $PM_{2.5}$, (b) PM_{10}, (c) PMC, (d) NO_2, (e) O_3, (f) CO and (g) SO_2 during the lockdown periods in 2020 compared to their corresponding periods in 2015–2019. (Source: Sokhi et al., 2021).

The decrease in CO and NO_2 were mainly attributed to the reduction in vehicular traffic, estimated at about 66%, while the increase in O_3 suggested a VOC-limited ozone production regime. Ozone maintained exceedances of WHO guideline values and Mexican standards during the pandemic.

Additional assessment of measurement data during the pandemic confirmed that the application of the restrictions led to reductions in ambient air levels of CO, SO_2, NO_2, PM_{10}, and $PM_{2.5}$, while O_3 concentrations were observed to increase (Hernández-Paniagua et al., 2021; Kutralam-Muniasamy et al., 2021; Peralta et al., 2021; Vega et al., 2021).

4.7.2.2. State of Hidalgo

Reductions in NO, NO_2, O_3, CO, PM_{10} and $PM_{2.5}$ concentrations were estimated during the COVID-19 contingency period with data from the Automatic Atmospheric Monitoring Network of the State of Hidalgo (INECC, 2021) Concentrations from March 1 to June 30, 2020, were compared with same periods of the previous years. Additionally, NO_2 and HCHO (as proxy for VOC) columns obtained from the TROPOMI sensor (on the Sentinel-5P satellite platform) were also evaluated. In Tula, comparison with the previous year 2019 showed reductions for O_3, NO_2, CO, SO_2, PM_{10}, $PM_{2.5}$ and formaldehyde (HCHO) concentrations of 19.5, 23.8, 3.8, 15.4, 13.8, 22.4 and 17%, respectively. Reductions on O_3 were attributed to decreases in NO_2 and HCHO during 2020, however the decrease was not proportional.

4.7.2.3. Toluca Metropolitan Area

Reductions in the levels of all criteria pollutants for Toluca during the period from March to May 2020 were observed. Levels of HCHO were analyzed using satellite products showing a reduction for HCHO when compared with the same period in 2019. The reductions on O_3, NO_2, CO, SO_2, PM_{10}, $PM_{2.5}$ and HCHO concentrations were 14.8, 24.3, 23.8, 36.6, 29.7, 32 and 16%, respectively (INECC, 2020).

The results obtained in these evaluations will be useful to determine the maximum reduction in concentration that can be reached when the main emission sources significantly reduce their activity and design strategies to mitigate emissions of atmospheric pollutants in the ProAire for the State of Hidalgo and the metropolitan area of the Valle of Toluca..

4.7.3. Changes in emissions generation in the MCMA during the COVID-19 pandemic

There is a significant knowledge gap about the actual impact on emissions during the pandemic, as well as the urgency to obtain and analyze this data. In Mexico City, as in the entire Megalopolis, this information will be relevant for air quality management. At the time of preparing this report, the only data available related to the evaluation of third-party data on reduced vehicular traffic, reduced fuel consumption and decreased gross domestic product.

The following information regarding the changes in emissions for the MCMA during the COVID-19 pandemic was provided by P. Camacho-Rodriguez (2022):

- Between April and May of 2020, Mexico City's traffic decreased drastically. According to *Tom Tom Congestion Index* data, an 80% reduction in congestion was achieved. Compared to 2019, the average reduction was 66%, this had impacts on vehicle emissions, both for the units that stopped circulating, and for the remaining units that circulated at higher speeds. In 2020 there were average reductions of 19% and 16% in gasoline and diesel consumption, respectively, compared to 2019 (PEMEX, n. d.).

Specifically, in April-June 2020, there were reductions of 40% and 30% in gasoline and diesel consumption, respectively, compared to the restrictions during Phase 3 of the COVID-19 pandemic.

- In the industrial sector, the Gross Domestic Product (GDP) in the MCMA decreased by 11% during 2020 (https://www.inegi.org.mx/programas/pibent/2013/#Tabulados). Some sectors such as textiles decreased between 33% and 50%, compared to 2019. On the other hand, during the pandemic there was an increase in plastics consumption (La Jornada, 2020), mainly due to their use in masks and non-woven synthetic fabric for medical personnel suits. The production of biological-infectious waste increased by up to 300%. In 2019 the production of coatings (for example, solvents, paints, automotive refinish) increased by 12%, while in 2020 the total production decreased by almost 4%.

- At the domestic (household) level, there was an increase in the use of detergents, surface cleaners, bleaches and disinfectants, aerosols and air fresheners, and deodorants (UNAM, 2021). This could have had an unquantified impact on increasing VOC emissions into the atmosphere. On the other hand, household LPG consumption decreased by ~5-7%.

- For biogenic emissions, an estimate from MEGAN (Model of Emissions of Gases and Aerosols from Nature) for the MCMA suggested an increase of VOC emissions by 22% during March-April 2020 compared to the same period in 2019. When compared to 2018, the increase was 29%.

In terms of the emission inventory, the estimates for 2020 are expected to provide relevant information during the pandemic; however, the estimates should not be considered in the emission trends due to their atypical nature.

4.7.4. Impact of COVID-19 on atmospheric chemistry in the Megalopolis

Considering that the meteorology and long-term variations may be an additional factor that influenced the possible changes associated with restrictions during the pandemic, Hernández-Paniagua et al. (2021) estimated the percentage change in concentrations during the pandemic, taking into account meteorological effects and the variability associated with long-term trends during the confinement in Phases 2 and 3. They performed the analysis of the anomalies estimated from the difference between the data predicted using truncated Fourier series and the data observed in some representative stations. Unlike the reductions described above, during Phase 2 of the lockdown, they observed significant decreases ($p < 0.05$) only in NO_2 with values between 10 and 23%, while O_3 increased between 16 and 40%. During Phase 3, they observed significant decreases in NO_2, PM_{10} and $PM_{2.5}$ with values of 43, 20 and 32%, respectively. In this phase, the concentrations of O_3 continued to increase; however, there was a greater spatial heterogeneity and the increases were significant only in two sites.

According to Hernández-Paniagua et al. (2021), in the case of CO, no important changes were observed in both phases, and for SO_2, a significant decrease was observed at a site representative of vehicular traffic only during Phase 3. The evaluation of satellite observations confirmed the decrease in NO_2 and the absence of changes in CO. The decrease in NO_2 was related to reductions in vehicular traffic, while they suggested that the possible increase in domestic emissions could offset the decrease in CO emissions attributed to vehicles. On the other hand, they proposed that reductions in NO_X emissions from motor vehicles were responsible for the increase in O_3 during Phase 2 because of lower O_3 titration. They suggested the little change in VOC concentrations was due to the absence or even increase in some emission sources (for example, domestic emissions) during Phase 2. During Phase 3, the further decrease in gasoline and diesel sales had some impact on the emission of VOCs, causing a stabilization in O_3 levels due to the combined reductions in NO_X and VOC emissions, resulting in a smaller reduction than during Phase 2. They also identified a spatial variability in the behavior of O_3 in Mexico City, with the largest increases in the center and south of the city. These results were consistent with the heterogeneity in O_3 production described by Zavala et al. (2020).

The increase in O_3 levels observed during the restrictions raises questions that will have to be addressed from atmospheric chemistry. Due to the non-linear chain reaction characteristics of photochemical reactions, O_3 concentration generally behaves in the opposite direction to changes in NO_X emissions. Nitrogen oxides have the effect of consuming free radicals, when their concentration in the ambient air decreases, the free radicals in the atmosphere are forced to react with other species and, under photochemical reactions, increase the production of O_3 (Wang & Li, 2021). To explain the situation observed in Mexico City, Peralta et al. (2021) suggested a change in the VOC/NO_X ratio from a VOC-sensitive regimen to a transitional or NO_X-sensitive regimen during the pandemic. According to these authors, this change could be caused by the drastic reduction in NO_X emissions and a possible increase in VOC emissions that offset the decrease in vehicle emissions, possibly coming from other sources that might include domestic sources, emissions evaporative emissions (anthropogenic and biogenic) and the increase in the use of cleaning products during the pandemic.

There is no doubt about the general improvement in air quality in Mexico City during the pandemic, as well as its positive impact on human health (Hernández-Paniagua et al., 2021; Kephart et al., 2021; Montiel-López et al., 2022) and other aspects of urban life (Estévez-Soto, 2021; Huerta, 2022; Vera-Valdés and Rodríguez Caballero, 2022). The experience during the restrictions confirmed the role of vehicle emissions, mainly private vehicles, and industrial emissions in the deterioration of air quality, but it also raised questions about the effectiveness of the mitigation strategies and current management scheme, as well as the urgent need for a more detailed analysis of what happened during the pandemic and derive lessons that contribute to the identification of new policies that complement or reorient the proposal in ProAire 2021-2030.

4.8. Lessons learned, knowledge gaps, and research needs

The following summarizes some of the main lessons learned, knowledge gaps and research needs regarding our current state of scientific knowledge on the sources and processes of formation and destruction of atmospheric pollutants in the MCMA and the other region of the Megalopolis described above.

4.8.1. Sources and processing of atmospheric pollutants

Lessons learned

- The MCMA-2003 and MILAGRO studies showed that, during the first decade of this century, the atmosphere of Mexico City was highly sensitive to VOCs in the urban core but could be VOC-or NO_X-sensitive in the surrounding region depending on meteorological conditions (Jaimes et al., 2016; Lei et al., 2007, 2008; Song et al., 2010). Recent study indicates that it is likely there is a substantial spatial difference in the sensitivity of O_3 to VOCs, including important differences in various areas of Mexico City and its periphery (Zavala et al., 2020).
- The levels of primary pollutant (CO, NO_2, SO_2) in the MCMA are highly sensitive to changes in anthropogenic emissions. This was demonstrated during the fuel supply problems in 2019 (García-Franco, 2020) and in the effects of the suspension of activities and mobility restrictions during the COVID-19 pandemic (Hernández-Paniagua et al., 2021; Peralta et al., 2021).
- Experience gained from changes in emissions resulting from drastic measures undertaken by the governments during the COVID-19 pandemic demonstrated that the formation of secondary pollutants such as O_3 was not controlled by changes in the primary pollutants in the proportions in which they were reduced. Furthermore, this highlights the importance of understanding the effects of meteorology and episodic contributions when analyzing air quality during large emission reductions (Sokhi et al., 2021). During the pandemic, the activity and distribution patterns of the vehicle fleet, as well as domestic and service activity, were modified; this could have had impacts on the concentration and variety of precursors and, consequently, on the chemical reactivity of the atmosphere.
- Non-linear relationships between precursor pollutants and the formation of secondary compounds (including their effects on peak concentrations) need to be further investigated under various meteorological conditions, along with climate change and socio-economic factors that could affect future air quality in the Megalopolis,
- The effects on precursor ratios and variations in the chemical composition of VOC emission profiles (both those from fossil fuel combustion and evaporative processes) on the formation of secondary pollutants should be investigated under various meteorological conditions in the Megalopolis.
- The production of secondary aerosols responds to changes in the composition of their precursors and the meteorology, therefore the sensitivity to the different gaseous compounds forming them under different meteorological contexts must be investigated.

Knowledge gaps

- What meteorological processes control the temporal and spatial distribution of gaseous and particulate pollutants in the lower atmosphere?
- What are the emerging factors (for example, regulations for new emissions, technological changes, social behavior) that intervene in the formation of pollutants in the Megalopolis and how can they be controlled?

- Has O_3 production changed in the MCMA? In which sectors of the city is O_3 production sensitive to VOCs or NO_X? Are there seasonal, weekly and diurnal transitions between chemical regimes?
- What are the current profiles and spatial distribution of mixtures of VOCs, semi-volatile organic compounds and persistent organic compounds, in the Megalopolis? What are the contributions of these compounds to the formation of O_3 and secondary organic aerosols (SOA)?
- What are the impacts of air pollution on the natural ecosystems and agricultural area of the Megalopolis?

Impacts of Tula-Tepeji industrial corridor on air quality in the MCMA and the Megalopolis region

- Why hasn't the fuel quality improved in the Tula-Tepeji corridor?
- Is it possible to establish a surveillance system for emissions from the industrial complex? What are the viable alternatives to reduce emissions from priority sources?
- What is the content of toxic compounds present in the plumes that carry air pollutants from Tula?
- How do emissions contribute to the disease burden associated with air pollution in and around Tula, as well as in plume trajectories?
- How do emissions from the industrial corridor affect other cities in the region (for example, Toluca, Pachuca, Tulancingo, San Juan del Río)?
- Is there any impact of atmospheric acid deposition on agricultural areas and conservation land in the entities of the Megalopolis?
- In addition to Tula-Tepeji corridor , are there other sources of anthropogenic contamination with regional impact?
- How do regional contributions of anthropogenic pollutants affect management objectives in the Megalopolis entities?

Regional scientific research

- The information available from monitoring indicates that some cities within the Megalopolis have pollution levels similar to and even higher than those observed in the MCMA.
- Air quality management programs require solid, up-to-date scientific support for the development and evaluation of control strategies to improve regional air quality.
- Scientific studies that allow us to understand the transport and transformation processes of pollutants are scarce outside of the MCMA. It is necessary to increase support to advance the study of meteorological phenomena related to the regional transport of pollutants, the identification of natural and anthropogenic sources with regional impact, the effects on health and ecosystems, the impacts on local management goals and the design of strategies to mitigate regional emissions.

- Information on the effects of pollution on human health outside the MCMA is scarce. It is a priority to know the situation in the other entities of the Megalopolis.
- Air quality monitoring in the region is limited. It is necessary to increase the spatial coverage of monitoring with a focus on priority pollutants in the different regions and improve the dissemination of information for health protection purposes, including non-urban areas and areas of interest for protection of crop and forest resources, modeling or validation of satellite data.
- It is necessary to promote institutional, financial, and technical efforts to achieve parity in monitoring, emissions inventory, modeling, scientific research, and management activities in the region under the coordination of CAMe.

4.8.2. Local meteorology and air quality

Lessons Learned

- It is necessary to study the characteristics of the planetary (or atmospheric) boundary layer and its effects on air pollution. Meteorological (such as wind, temperature and humidity) and aerosol profilers have proven to be a robust tool to measure and investigate with high temporal resolution the behavior of various variables in the planetary boundary layer. The study of the properties of the boundary layer requires multiple techniques, combining remote sensing with radiosonde observations, where each of them will provide different information about processes of mixing, ventilation, and dispersion.
- Open questions remain about the different processes in the boundary layer that control mixing and the surface concentrations of pollutants, as well as the interaction of boundary layers between neighboring basins, which is why different synchronous instruments at multiple locations are needed to better understand its temporal and spatial variability.
- The studies presented in Section 4.4.2 describe the mixed layer average height, its daily and seasonal variability, and potential uses of the ceilometer to better understand the relationship between these characteristics and air quality. However, questions regarding how this interaction influences extreme pollution events in the context of a changing climate remain to be investigated.
- The possible effects of radiation on the formation of O_3 is a relevant aspect for management; it has been observed that with the increase in solar radiation, the production of O_3 also increases.
- The ProAire 2021-2030 considers a reduction in aerosols, however, this could induce an increase in O_3 concentrations due to the increase in solar radiation that reaches the surface. On the other hand, the changing climate could impact the formation processes of secondary pollutants.

Knowledge gaps and research needs

- What is the intensity of the urban warming in the different urban conglomerates of the Megalopolis?
- How does urban warming affect the micrometeorology of the cities of the Megalopolis?

- What impacts does urban warming have on the regional climate and atmospheric chemistry?
- Should management plans consider the effects of the urban warming on pollutant reduction goals? Should they include actions for their mitigation?
- What are the expected effects of climate change on meteorology and air quality in urban and non-urban regions in the entities that make up the Megalopolis?
- How do global, regional and local meteorological changes influence episodes of high urban pollution?
- The available evidence indicates with some degree of certainty that the increase in temperature will bring about changes in the chemistry of the atmosphere and in the production of O_3, however, there is great uncertainty in the magnitude. The concept of climate penalty refers to the possible increase in the concentration of O_3 in environments with high levels of its precursors. In this sense, how will the climate penalty affect the reduction goals of the different management plans? Should management plans include climate penalties?

4.8.3. Short-lived climate forces

Black carbon emissions from on-road and off-road diesel vehicles

- The results of field studies in the MCMA highlight the need to use databases of locally obtained emission factors for developing countries with the aim of reducing the uncertainty in the emissions estimates and improving the evaluation of effectiveness of emissions reduction measures.
- Estimating emissions from in-use off-road vehicles for construction and agriculture is challenging because the available emission factor dataset is considerably smaller compared to that available for on-road vehicles.
- Due to their durability, off-road vehicles remain in service for several decades and therefore their relative contributions to emissions increase over time, while emissions from on-road vehicles continue to decline due to technological improvements. Therefore, off-road vehicles are potentially large contributors to BC emissions in many parts of the world, highlighting the importance of designing emissions control strategies and a strong need to increase the emission factors databases for off-road vehicles through field studies.

Methane emissions from wastewater treatment plants

- Sewage and treatment plants are a major source of CH_4 and N_2O.
- Adopt treatment systems with low energy consumption since this represents more than 60% of total CH_4 emissions.
- Improve the operation of primary sedimentation (frequent purges).
- An adequate treatment of the sludge must be given, preferably one that considers the production and use of biogas.

- The Tier 1 methodologies of IPCC (2006 and 2019) represent an inaccurate tool as they underestimate emissions.
- It is important to determine specific emission factors to more accurately estimate GHG emission inventories. Based on this, more effective mitigation policies can be identified and applied.

Methane emissions from livestock enteric fermentation

- It is necessary to continue conducting studies on CH_4 emissions from enteric fermentation of cattle under different production and feeding systems in Mexico, including other ruminant species such as sheep and goats.
- Strengthen studies to determine specific CH_4 emission factors for manure management in Mexico.
- It is necessary to design mitigation strategies for CH_4 emission from enteric fermentation applicable on a commercial scale.
- Strengthen studies of specific N_2O emission factors for Mexico. Progress has been minimal on this topic.
- Perform life cycle analysis of GHG originating from the agricultural sector.

4.8.4. Air quality modeling and forecasting

Improve model development and application

- Employ inverse modeling to complement the evaluation of bottom-up inventories, considering their potential to improve the spatial and temporal resolution of the inventory and to estimate the location and intensity of known and emerging emission sources.
- Allocate resources to reduce uncertainty in inventories, improve profiles and estimates based on measurements, and advance knowledge about the participation of VOCs in the production of aerosols and gaseous pollutants of photochemical origin.
- Obtain data on the characteristics of primary aerosols for different representative environments of the Megalopolis. Obtain meteorological and air quality data outside of the urban areas.
- Explore the best model parameterizations for the different regions of interest in the Megalopolis, produce or obtain data with the appropriate resolutions for input and evaluation of the model.
- Consider modeling needs within research projects and management policies, and increase the spatial and temporal resolution of air quality and meteorology measurements. Include modeling needs in the design of monitoring systems.
- Strengthen the modeling capabilities of the region through the construction of an ensemble of models that includes the currently available models (for example, SEDEMA, ICAyCC-UNAM, Querétaro), as well as possible future developments.

- Support the efforts of Mexico City to ensure continuous improvement of its forecasting system and guarantee its sustainability.
- Move towards the assimilation of data from satellite products and other observation networks and profilers, which can be used for both case studies and forecasting. With adequate computing capacity, it is possible to move from limited area models to multi-scale global models and thus study atmospheric pollution in the context of climate change.
- Coordinate inter-institutional efforts in the production, management, and treatment of data to generate useful products for air quality management.
- Apply machine learning algorithms to improve the physical parameterizations of the models, in the estimation of emissions, in the analysis of satellite images and model outputs to adjust the results, and thereby obtain better predictions.

Strengthen human resources:

- Train research personnel in the area of data assimilation, use of satellite information, evaluation of models, evaluation of the application of machine learning in the processes carried out by the models, as well as in the evaluation and post-processing of the products obtained in modeling.
- It is necessary to increase the number of technical personnel for the maintenance of supercomputing infrastructure and use of the software.

Develop infrastructure

- Centralization of the computer infrastructure and virtualization of the provision of services to provide entities or institutions with computing capabilities, or allocate resources for the acquisition of computer facilities to the entities of the Megalopolis.

4.8.5. COVID-19 impact on air quality

Knowledge gaps and research needs

- It is necessary to have accurate estimates of NO_X and VOC emissions in the MCMA and surrounding regions in order to understand the changes in the formation of O_3, $PM_{2.5}$ and other secondary pollutants during the COVID-19 lockdown period.
- The experience during the pandemic showed a new scenario that confirmed the complex interaction between emissions, meteorology and atmospheric chemistry in the urban atmosphere of the MCMA.
- It is necessary to understand how the chemical composition of VOCs changed during the pandemic.
- There is sufficient evidence that, during COVID lockdown, the transportation sector was strongly impacted, substantially reducing congestion, but at the same time, increasing the traffic of home delivery vehicles. In general, the industrial sector also decreased its activities, some industries more than others. Food preparation activities at home, in informal sales and the restaurant sector were modified. However, emissions from products

for personal use, household products, paints, waterproofing agents, domestic garbage, waste, disinfectants, cleaners, among others, increased. It is necessary to evaluate how the service and commercial sectors have modified their operations.

- It is necessary to understand how the contribution of domestic emissions (for example, cleaning products, food preparation, burning and leaking of LPG and CNG) and from sources other than automobiles and industry (for example, agricultural and forest fires, biogenic emissions, evaporative emissions from other sources) contribute to air pollution and influence the production of O_3 and secondary aerosols.
- Based on what was observed during COVID-19 restrictions in the MCMA, the results suggest that reductions in emissions from vehicles and industries caused a decrease in the concentrations of primary pollutants in ambient air, however, no reduction in O_3 concentrations was observed. Why? How would this affect the objectives of air quality management and the actions that are applied during environmental contingencies?
- Based on the experience during the pandemic, how do changes in the vehicle fleet and domestic activity modify the chemical reactivity of the atmosphere?
- Given the observed reductions in $PM_{2.5}$, there is a need to understand how the reductions in precursor emissions modified the chemistry of the secondary formation of aerosols.
- Regional transport of air pollutants during lockdown period:
    - How did the emission sources from nearby states contribute to air pollution levels in the MCMA?
    - How did the emissions from the MCMA contribute to pollution levels in nearby states?
- A comprehensive characterization of the atmospheric reactivity, radical budget, and secondary pollutant formation during the lockdown period using modeling tools is needed to understand the air quality during the lockdown period.
- The availability of comprehensive VOC speciation during the COVID-19 lockdown will allow evaluation of changes in OH-VOC reactivity.
- A thorough characterization of the local and regional meteorology during the lockdown period is needed to evaluate any potential ventilation enhancement (that is, windy conditions) or favorable condition for photochemistry (that is, more intense solar radiation).
    - What were the meteorological conditions that contributed to high $PM_{2.5}$ and O_3 production/accumulation during high pollution days?
    - What regional and local wind patterns helped to disperse the pollutants during the lockdown?

CHAPTER 5. PUBLIC HEALTH STUDIES AND AIR POLLUTION IN THE MEGALOPOLIS

5.1. Introduction

The main objective of actions aimed at improving air quality is to reduce the exposure of inhabitants to air pollutants. According to the World Health Organization (WHO), air pollution is the world's most pressing environmental health crisis. The combined effects of ambient (outdoor) air pollution and household air pollution are associated with about seven million premature deaths per year (WHO, 2022).

Information on how human health responds to exposure to air pollution can be obtained from different sources: epidemiological studies, controlled exposure studies, and research using laboratory animals or *in vitro* cells and tissues. Epidemiological studies are used to determine whether air pollution or a source of air pollution poses a risk to human health, or to characterize the relationship between exposure level and response, and to examine the responses of potentially sensitive groups to exposure to pollutants. These studies are very useful in assisting decision-makers in the design of management strategies or determining whether a particular control strategy has had any impact. On the one hand, studies with human subjects exposed to well-characterized atmospheric test concentrations provide detailed information on clinical responses to inhaled pollutant(s). On the other hand, laboratory studies using animal models are very useful to study the harmful properties of different air pollutants. The direct effects of pollutants on cells and tissues, whether animal or human, can be studied in *in vitro* experiments under different exposure conditions. Taken together, the studies described above are necessary and fundamental to evaluate the mechanisms of action of various air pollutants. The process allows air quality management to incorporate the best available scientific evidence into public health policies.

Adverse health effects include reduced lung growth and respiratory function, respiratory infections, and aggravated asthma in children, while ischemic heart disease and stroke are the most common causes of premature death in adults. There is emerging evidence of other effects such as lung cancer (Santibáñez-Andrade et al., 2019), diabetes, neurodegenerative diseases, and psychological effects. A new study in the United States of America indicated that long-term exposure to low levels of air pollution, even below those allowed by some existing regulations, may be causing tens of thousands of premature deaths among the elderly and other vulnerable groups (Yazdi et al., 2021).

The body of evidence on air pollution and health has led to increasingly large risk estimates so the WHO proposed stricter air quality guidelines in September 2021, modifying those in place since 2005 (WHO, 2021a, 2021b); this was followed by updated Mexican air quality standards NOMs (see Table 1.1, Chapter 1). This becomes more relevant in the Megalopolis region, which presents significant air pollution problems that are reflected in frequent non-compliance with air quality standards, health impacts, direct and indirect economic costs, and damage to ecosystems. Health impacts can be exacerbated for the most vulnerable population groups, such as the elderly, pregnant women, children, those with chronic illnesses or those with weakened immune systems.

Hence it is important to review the current state of knowledge on studies of public health and air pollution in the Megalopolis, and to assess their progress and scientific challenges.

Improvements in air quality are directly or indirectly associated with public health benefits by reducing acute and chronic exposure to air pollutants. For example, a recent study (Dockery et al., 2019) concluded that improvements in air quality in Mexico City between 1990 and 2015 prevented approximately 22,500 premature deaths (SPH-Harvard, 2016). For each decrease of 10 $\mu g/m^3$ in the annual mean of $PM_{2.5}$, an increase in life expectancy of 0.89 ± 0.38 years was observed. For every 10 ppb decrease in the average maximum O_3 concentration, an increase of 0.24 ± 0.08 years was observed. There was no difference in the estimated benefits of $PM_{2.5}$ reduction between men and women, however for O_3 men showed an almost three times greater association. Overall, air quality improvements in Mexico City over the past 25 years have produced an estimated 1.3-year increase in life expectancy attributable to reducing $PM_{2.5}$ exposure, and a further increase in life expectancy of 1.9 years attributable to reducing O_3 exposure.

In Mexico and particularly in the Megalopolis, the Programs to Improve Air Quality known as ProAire are used, which combine the strategies, actions, and procedures to prevent, control and address poor air quality, prepared from a previous diagnosis based on the available data on air quality, physiography, meteorology, health, and management, considering the technological and human capacities of the entity. These programs also include the protocol for dealing with environmental contingency episodes, known as the Atmospheric Environmental Contingency Program (PCAA, *Programa de Contingencias Ambientales Atmosféricas*) and in the case of Mexico City as the Program to Prevent and Respond to Atmospheric Environmental Contingencies (PPRECAA, *Programa para Prevenir y Responder a Contingencias Ambientales Atmosféricas*). These protocols seek to organize control actions during episodes of poor air quality, when exposure and concentration levels exceed the established limits and put human health at risk (see Section 6.4.4 about PPRECAA, Chapter 6).

Since the 1980s in Mexico, specialized studies have been carried out to improve knowledge about the impacts of air pollutants on health.. A tangible example is the studies on the effects on human health due to exposure to environmental lead (Pb) derived from the use of tetraethyl lead ($Pb(C_2H_5)_4$) as an additive in gasoline. The results of these studies were important in changing the official standards in which Pb was removed from fuels. Other studies that have been carried out in Mexico include the relationship between air pollutants and asthma, mortality rates, cardiovascular effects, lung development in children and, more recently, the relationship between pollution levels and the health impacts of COVID-19. In addition to health impacts of criteria pollutants, exposure studies to ultrafine particles and unregulated air pollutants, such as polycyclic aromatic hydrocarbons (PAHs), have been conducted in Mexico. This chapter presents the results of the Virtual Workshop and summarizes the current state of knowledge of studies on public health and air pollution, the lessons learned, and the scientific challenges on the topic. Some of the studies related to the impacts of COVID-19 are described in more detail in Chapter 4.

5.2. Current state of knowledge on the impacts of air pollution on public health in the Megalopolis

Epidemiological and toxicological studies on the health impacts of air pollution have traditionally focused on pollutants such as O_3 and particulate matter. Exposure to particulate matter has been associated with pulmonary, cardiovascular, and neurological diseases, and in general with chronic diseases, such as metabolic diseases and cancer. Due to their minute size, fine particles with diameters less than 2.5 µm ($PM_{2.5}$) and ultrafine particles with diameters less than 0.1 µm ($PM_{0.1}$) can penetrate deeply into the respiratory tract. Since these particles are associated with combustion processes, they tend to be highly toxic due to the complex mixture of their chemical composition. It is known that particulate matter has a greater impact than O_3 on mortality, although O_3 has greater impacts on the morbidity of the exposed population. This section summarizes the main results of recent studies on the health impacts of air pollutants in Mexico.

5.2.1. Epidemiological studies of exposure to air pollutants

A longitudinal study[1] of the association between prenatal exposure to $PM_{2.5}$ and the neurodevelopment of children under two years of age showed that exposure to $PM_{2.5}$ during pregnancy affects language function performance in early childhood (Hurtado et al., 2021). The magnitude of the association is maintained even after controlling for stimulation at home.

Ugalde-Resano et al. (2022) estimated the risk of emergency medical visits in Mexico City associated with exposure to air pollutants regulated by the Official Mexican Standards (criteria pollutants[2]), except for lead, by using the number of visits for cardiovascular emergency. The study was ecological , that is, the unit of analysis was the municipalities and not the individuals, with retrospective analysis[3] of time series of daily consultations for cardiovascular emergencies. The results indicated a percentage increase in the number of consultations for cardiovascular emergencies associated with exposure to criteria pollutants. Future studies could include individual data such as socioeconomic status or other potential factors, such as medical history and exposure to other pollutants.

International scientific evidence has suggested that air pollution is a risk factor for diabetes (type 1, 2 and gestational). Cross-sectional[4] but also longitudinal epidemiological studies, developed mainly in populations from developing countries, have confirmed this association. Through a

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[1] In a longitudinal study, researchers make multiple observations of the same subjects over a period of time, which can last several years. Most longitudinal studies examine associations between exposure to known or suspected causes of disease and subsequent morbidity or mortality.

[2] Criteria pollutants are air pollutants for which acceptable concentration limits have been set on the basis of available information on health effects of each pollutant (see Table 1.1, Chapter 1).

[3] A retrospective analysis is initiated after individuals have developed the disease or characteristic under investigation and is directed backward in time to determine the status of subjects before disease onset.

[4] A cross-sectional study measures the prevalence of changes in health or health determinants, or both, in a population at a given time or over a short period.

cohort study[5], exposure to air pollution by $PM_{2.5}$ and NO_2 and the incidence of diabetes in Mexico were investigated (Cervantes-Martínez et al., 2022). The results showed an increased risk of developing type 2 diabetes due to medium and long-term exposure to $PM_{2.5}$ and NO_2. For the medium term, for each increase of 10 units of $PM_{2.5}$ (µg/m^3) and NO_2 (ppb) the risk of diabetes increased by 72% and 52% respectively. For annual and biannual exposures, the increases in risk were 88% and 70% for $PM_{2.5}$ and 44% and 39% for NO2, respectively. The results persisted in different sensitivity analyses, including the evaluation of the exposure only in the residence of the participants and the evaluation of a stricter definition of the incident case of diabetes, among others.

Two cohort studies focused on evaluating the effects of air pollution on metabolic diseases in children. In the first study, pregnant women were recruited to evaluate the effect of prenatal NO_X exposure and its effect on birth weight (Mendoza Ramírez et al., 2018). The results showed that 50% of the children were exposed pre-gestational to various environmental concentrations of NO_X and a significant decrease in birth weight was observed due to exposure to increased NO_X, even when considering height and passive smoking in the mother and the gestational age and gender of the child. In the second cohort study, NO_X exposure from the prenatal stage and in developing children from the age of 7 to 12 years on cardiovascular risk was investigated through the waist-height ratio. It was found that children in the second and third tercile of NO_X exposure were more likely to have a waist-height ratio above the limit value for cardiovascular risk compared to the lowest tercile (Ceja Esparza, 2021).

Tamayo-Ortiz et al. (2021) estimated the $PM_{2.5}$ concentrations using a hybrid exposure model based on surface and satellite data, land use and meteorological information, to evaluate the impacts in representative samples of the population, stratified by age groups (0-9, 10-19 and ≥20 years) from the data of the National Health Survey and Nutrition (ENSANUT, *Encuesta Nacional de Salud y Nutrición*) carried out in 2006 and 2012. They found that exposure to $PM_{2.5}$ was associated with higher probability of obesity and in all age groups, but with more robust results in adolescents. For every 10 µg/m^3 increase in $PM_{2.5}$, the probabilities of obesity were 3.53 in 2006 and 3.79 in 2012. On the other hand, Pérez-Humara et al. (2020) conducted a longitudinal study in overweight and obese adolescents from 9 to 21 years of age in Mexico City to evaluate the associations between short-term exposure to environmental O_3 and metabolic activity, using three indices: acylcarnitine, amino acids and a mixed index . Their results found a significant association between higher O_3 concentration with lower scores in the amino acid index and in individual amino acid concentrations, suggesting a lower metabolic activity in this sector of the young population.

Children are particularly vulnerable to exposure to suspended particles since their lungs and immune system are developing; they have a higher respiratory rate, which increases the inhaled dose of toxins, and smaller diameter airways, which increase the Relative airflow resistance. The results of the Study of Health and Air Pollution in Latin America (ESCALA, *Estudio de Salud y Contaminación Atmosférica en Latina América*), which included four large urban centers (Mexico City, Mexico; Santiago, Chile; Sao Paulo and Rio de Janeiro, Brazil), showed the effects that pollution atmospheric has on respiratory mortality among the child population (Gouveia et al.,

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[5] A cohort study is a longitudinal study that follows two groups of previously selected individuals, in which a comparison of the frequency of occurrence of an event is made by comparing both groups, one of which has been exposed to a factor that it is not present in the other group.

2018). Even though the daily number of deaths was relatively low in all cities and the results varied, the meta-analysis found statistically significant impacts of air pollution on infant and child mortality, with more consistent results for PM_{10}, which showed positive and significant risks than for O_3, which presented fewer estimates of positive effects.

Barraza-Villareal et al. (2008) evaluated the effects of exposure to $PM_{2.5}$ in a cohort of 158 asthmatic children living in three densely populated districts of the metropolitan area of Mexico City: Iztapalapa, Iztacalco and Nezahualcóyotl;, where high levels of traffic-related emissions were the main source of pollutants. Their results showed that $PM_{2.5}$ exposure caused acute airway inflammation and decreased lung function in both asthmatic and non-asthmatic children. Téllez-Rojo et al. (2020) used satellite observations with optical depth data to estimate the concentration of $PM_{2.5}$ and interpolated data from $PM_{2.5}$ measurements, made by the monitoring stations of the Automatic Atmospheric Monitoring Network (RAMA), to estimate the average two-week exposure to $PM_{2.5}$ in the metropolitan area of Mexico City. Their results showed a significant positive association between short-term exposure to $PM_{2.5}$ with increased reports of acute respiratory symptoms in children.

5.2.2. Toxicological studies of particulate matter

Even though many of the mechanisms are unknown, evidence has been found between exposure to suspended particles of the fine fraction with lipid alteration and an increase in stress hormones that promote metabolic alterations, the induction of damage to deoxyribonucleic acid (DNA) and an increase in the oxidative stress, the effects on the induction of mediators, early kidney damage and antioxidant and immunological imbalance, and neuroendocrine disturbance or imbalance of the autonomic nervous system or heart rate affected by binding to receptors in lung tissue or nerve endings (De Vizcaya- Ruiz, 2022).

De Vizcaya-Ruiz et al. (2006) characterized the biological effects of the particulate matter obtained in the dry-cold and dry-hot seasons at various points in the Megalopolis. The results showed the presence of cell death induction in human alveolar epithelial cell cultures related to particle size, site location, and season of the year. They also found evidence of the induction of DNA damage in human cells related to all particulate matter samples, as well as a higher oxidative capacity mainly due to the fine fraction. Particles collected north of the city showed higher metal and biological content, induction of apoptotic cell death, and more extensive DNA damage. In another toxicological study, the effect of the chemical composition of the particulate matter was investigated (Gutiérrez-Castillo et al., 2006). The results showed effects of cell death and DNA damage depending on the spatial and temporal distributions of the particulate matter collection site, as well as its size and oxidative reactivity. Subsequent toxicological studies have confirmed the relationship between exposure to PM and the induction of damage at the cellular and DNA level, as well as the exacerbation of oxidative stress (Sánchez-Pérez et al., 2009; Chirino et al., 2010; Quezada- Maldonado et al., 2018, 2021; Corona-Vázquez et al., 2019; Maher et al., 2020).

In a study on the association between increases in morbidity and exposure to organic PM_{10} compounds, the correlations between mutagenic compounds in organic mixtures with different polarities and their mutagenic responses in bioassays were investigated (Villalobos-Pietrini et al., 2007). This study focused on polar organic compounds such as polycyclic aromatic hydrocarbon compounds (PAHs) in the particulate phase, which originate from gaseous precursors resulting from incomplete combustion of mobile sources and biomass burning. These compounds were correlated with mutagenic effects depending on their polarity. In a study of trends in carcinogenic PAH compounds, Amador-Muñoz et al. (2020) showed reductions of up to 40% of PAHs in $PM_{2.5}$ in the 2016-2017 period compared to 2006.

Exposure to particulate matter has been linked to underlying mechanisms of lung damage and cardiovascular disorders through toxicological studies using experimental animal models. These studies make it possible to establish the physiopathological mechanism of a disease associated with concentration and exposure time. Falcon-Rodriguez et al. (2017) found that exposure to suspended particles could act as an adjuvant in allergic asthma in previously sensitized guinea pigs. They observed metaplasia of mucous cells in the bronchial epithelium, which increased when sensitized animals were exposed to $PM_{2.5}$ particles from Mexico City. In a toxicology study in rats exposed to particulate matter, the results showed induction of inflammatory mediators in the lung in response to short-term or acute exposure to $PM_{2.5}$ and $PM_{0.1}$, but not to particles smaller than 10 µm (PM_{10}) (Aztatzi -Aguilar et al., 2018). Activation of the receptor responsible for vascular balance and blood pressure in the lungs and heart of rats was also observed due to exposure to $PM_{2.5}$ and $PM_{0.1}$ (Aztatzi-Aguilar et al., 2015) and that sub-chronic exposure to $PM_{2.5}$ caused early kidney damage, as well as an antioxidant and immune imbalance (Aztatzi-Aguilar et al., 2016).

Another toxicological study with experimental models in animals with exposure to $PM_{0.1}$ showed that the induction of placental stress during intrauterine life caused epigenetic damage and cardiovascular damage that manifested itself in mice when they reached adulthood (Morales-Rubio et al., 2019). The results suggested that exposure to particulate matter contributed to the development of chronic diseases in body systems that went beyond the lungs and that impacted the development of cardiovascular diseases (Morales-Rubio et al., 2022).

A study evaluated the participation of extractable organic matter (EOM) of $PM_{2.5}$ as a cause of alterations in biomolecules and the production of pulmonary surfactant (Déciga-Alcaraz, 2022). The results showed that type II pneumocytes presented morphological alterations after exposure by EOM, which generated an increase in the production of total proteins. Type II pneumocytes play an important role in the lung since, in addition to producing alveolar surfactant, they have the ability to regenerate, proliferate, and differentiate into type I pneumocytes to restore damage caused by external agents. The results indicated that exposure to EOM caused alterations in the production of surfactant of type II pneumocytes, which could result in the cells being susceptible to viral, bacterial, or fungal infections. These results open a door for research on the toxicological effects caused by exposure to EOM on pulmonary surfactant that have not yet been fully described.

5.2.3. Studies of exposure to air pollutants

In a study of personal exposure to particle pollution on public transportation, Velasco et al. (2019) used portable instruments to investigate the effect of public transportation mode on exposure, studying a route in a crowded area of Mexico City. The modes of transport investigated were the Metro and Metrobús systems, taxi, Uber, walking, and by bicycle. The air-conditioned Uber was identified as the cleanest mode of transportation, with exposure concentrations below those recorded at a reference site far from the road, while the Metro system recorded the highest particulate concentrations. It was observed that personal exposure was highly influenced by emissions from informal street food stalls. It was also found that cyclists and pedestrians inhaled the highest concentration of particles, compared to other modes of transport. The Metrobús or Metro mode of transport presented lower concentrations compared to walking and traveling by taxi. About 80% of the particles in the different modes of transport measured less than 70 nm, the average being 40 nm.

A recent study investigated chronic exposure to unregulated pollutants and its impact on breast cancer, focusing on understanding relationships with endocrine-disrupting pollutants such as phthalates (Segovia-Mendoza et al., 2022). There is controversy about the relationship between exposure to carcinogenic compounds PAHs and the development of breast cancer. It is currently known that the main association is due to the interaction of various contaminants with estrogen and progesterone receptors. In this study, the impact of phthalates associated with the manufacture of plastics, medical supplies, cosmetics, containers, nail polish, food packaging, plastic toys, etc., was evaluated. And its alteration of different metabolic pathways and breast cancer. Differences were found in the concentrations of the parental phthalates in patients with mammary tumors. Depending on the type of tumor, they could have higher levels of some phthalates. The results indicate that exposure to phthalates may be part of the comorbidities that could modify the susceptibility and even the mortality of patients with breast cancer.

There is controversy about the relationship between exposure to unregulated carcinogens such as PAHs and the development of breast cancer. It is currently known that the main association resides in its interaction with estrogen and progesterone receptors.

Ultrafine particles or nanoparticles have been associated with various health problems (Calderón-Garcidueñas et al., 2021), there is growing evidence suggesting that ultrafine particles may have adverse impacts on the health of the inhabitants of Mexico City. Cognitive and smell deficits, gait and balance disturbances, auditory evoked potentials of the brainstem, and sleep disorders have been observed in young residents of Mexico City (Calderón-Garcidueñas & Ayala, 2022).

Exposure to $PM_{2.5}$ and nanoparticles was associated with significant motor and cognitive decline in young adults, possibly as a result of complex interactions between gateways, nanoparticle chemical composition, protein interactions, and eventual cell damage in brain cells (Calderón-Garcidueñas et al., 2020). The presence and accumulation of nanoparticles from combustion and friction in the left ventricle of young subjects chronically exposed to high concentrations was associated with significant damage to the neurovascular unit and evolving Alzheimer's disease (Calderón-Garcidueñas et al., 2019). In the case of cardiovascular diseases, the presence of iron-rich nanoparticles within the myocardial mitochondria seems to be associated with mitochondrial dysfunction and excessive formation of reactive oxygen species through the iron-catalyzed Fenton reaction. Myocardial iron overload from inhalation of airborne metal-rich nanoparticles is a plausible and modifiable environmental risk factor for cardiac oxidative stress and cardiovascular disease (Maher et al., 2020). These results suggest the need to control and monitor the presence of nanoparticles in urban air.

Meteorology in combination with urban morphology, the characteristics of pollutant emission sources and the chemical transformations that occur in the atmosphere of cities, produce a heterogeneous distribution of air pollution with multiple microenvironments interacting within the urban context. The composition of the air can vary within the same city and during the day.

Depending on the mixture and concentration of pollutants, they can have synergistic, antagonistic or indifferent effects on human health, making it difficult to assess the impacts on public health. The Megalopolis lacks studies on the synergistic effects of exposure to the urban mix that consider other chemical species in addition to the criteria pollutants.

5.3. Cost-benefits and risk communication

Policies to regulate emissions and levels of pollution in the atmosphere can have strong economic or social impacts. Its implementation is not easy and requires economic justification of its actions and interventions before the affected sectors and society in general. The justification is based mainly on the assignment of a monetary value to the expected benefits in public health, the well-being of the population, food safety and the environment. In economic terms, the optimum level is at the point where the cost of reducing emissions equals the benefits of the resulting reduction in damage. Some recent examples of cost-benefit analysis in the Megalopolis are given in Section 6.4.6 of Chapter 6.

On the other hand, continuous communication of pollution risks based on monitoring data is the best strategy to prevent impacts on the health of the population in the face of deteriorating air quality. The use of air quality indices has resulted in an effective risk communication tool in major urban centers around the world. Mexico developed the Air and Health Index that harmonizes the way in which the state of air quality and its effects are reported. Mexico City also uses the Risk Index for Susceptible Persons (IRPS) based on evidence of the health effects of multiple pollutants. Both indices are described in greater detail in Section 6.5 of Chapter 6.

5.4. Lessons learned

It is important to mention that some of the results of health studies on particulate matter and O_3 were used to formulate some of the policies and programs for air quality control in the Megalopolis. However, key questions and issues remain regarding the health effects of air pollutants and the quantification of the costs and health benefits derived from the control of key emission sources. It is necessary to better understand the relationship between chronic and acute health effects that are aggravated by exposure to poor air quality. This section presents a summary of the lessons learned from recent studies of the health impacts of air pollutants in Mexico.

- ***Incorporation of results from health studies in air pollution control programs***. The results of recent studies show evidence of correlations between various types of morbidity and concentrations of air pollutants, mainly for $PM_{2.5}$. Current research on health impacts include effects at the cellular and deoxyribonucleic acid (DNA) levels, chronic lung diseases, different types of cancer, metabolic diseases, neurological effects, concentration-response functions, and the statistical value of life. There is a wide range of studies that provide evidence of the health impacts of air pollutants. However, it is important that these results can be incorporated as support for the design of regulations and programs to reduce air pollution. For this, the scientific community in Mexico must address the issue of representativeness and robustness of the results, so that they can contribute to the establishment of a scientific basis for the design of air quality control strategies.

Furthermore, mechanisms must be created to reduce the gaps for efficient integration of the results of health studies in the design of public policies, including activities for prevention, and the reduction of exposure to contaminants that are harmful to health.

- ***Dissemination of information to reduce exposure.*** Another substantial advance has been the real-time dissemination of air quality conditions and their possible impacts on the health of the population of the Megalopolis, based on the information from the available atmospheric monitoring networks. The continuous dissemination of information through applications, public reports, news media and social networks helps the population to make informed decisions to carry out their activities in indoor and outdoor spaces that reduce exposure to air pollutants, thereby improving people's health and quality of life. These actions have been key before, during and after the declaration of O_3 and particulate matter environmental contingencies in the PCAA programs to alert and inform the population. Information dissemination activities are part of the actions listed in the ProAire for the Megalopolis.

- ***Epidemiological evidence indicates that there is no safe exposure threshold for particulate matter and gaseous pollutants.*** There is evidence that suggests that the health effects of air pollution are not related to specific limits. The mix of air pollutants in urban areas can be quite complex, and their chemical characterization and health effects present significant challenges. This suggests that exposure to concentrations of particulate matter, even below the WHO air quality guidelines, can be hazardous to the health of the population.

5.5. Key science questions

- ***Representativeness of morbidity studies.*** There is a need to better understand the representativeness of the results obtained in morbidity studies, such as metabolic diseases, diabetes, and effects on neurological development, among others. It is important to know if the results obtained in the morbidity studies are robust enough to support the development of new initiatives for public policies and new regulations.

- ***The integration of the results of health studies in the design of public policies***. An issue that must be addressed by the scientific community and decision makers is the establishment of mechanisms to integrate the results of health studies into the public agenda. Beyond the scientific establishment of the relationships between effects on morbidity and exposure to air pollutants, it is vital that the information generated assist the development of air quality improvement strategies.

- ***Health studies for exposure to other pollutants.*** Traditionally, health studies have focused on criteria pollutants such as O_3 and particulate matter. However, the population in urban areas is exposed to complex mixtures of gases and particles. Thus, there is a need to expand studies of the health effects of exposure to chemical mixtures of VOCs, PAHs, toxic pollutants, metals, nanoparticles, emerging pollutants[6], and the complex combinations of compounds in particulate matter. These investigations are necessary not only for studies of mortality but also for morbidity.

- ***Exposure studies***. It is necessary to increase and improve our understanding of the characteristics of exposure to air pollutants. This also includes improving the mechanisms to generate the information necessary for exposure studies at the local and regional level. It is important to determine if the results of those studies can be used to improve our understanding of exposure to air pollutants.

- ***Integration of other methodologies***. Improving exposure assessment also implies strengthening the collaboration between the agencies that produce the information, as well as integrating other data generation methodologies such as satellite information, personal monitoring, emissions inventories, and air quality modeling. The integration of these methodologies would make it possible to substantially improve the availability of the databases necessary to understand exposure to air pollutants.

5.6. Scientific challenges and recommendations

- ***Toxicological profiles***. The results of the toxicological studies show evidence of biological causes and mechanisms that can explain acute, chronic, and trans-generational health impacts. There is, however, the challenge of determining the toxicological profiles (e.g., organic content) of particulate matter in different parts of the Megalopolis. It is important to know the regional differences in toxicological profiles to correlate them with specific health impacts for population groups in the Megalopolis, as well as chemical products from reactions with other pollutants.

- ***Impacts due to mixtures of air pollutants and pathogens.*** The study of the health impacts of mixing or combining air pollutants with pathogens (for example, viruses) is still an important challenge that must be addressed by the scientific community. This also includes the need to develop the necessary toxicological methods to use for addressing the problem. The complexity of this challenge increases to the extent that the variability of the spatial distributions of pathogens and air pollutants are great within the Megalopolis.

- ***Interaction between climate change, air quality and health.*** There is a complex interaction at multiple scales between climate change and air quality, yet the connection between local air pollution sources and the emissions that drive climate change is very clear. In addition to adverse effects of anthropogenic pollutants on human health, naturally occurring air pollutants such as pollen, biogenic volatile organic compounds, smoke from wildfires and windblown dust can be influenced by climate change and become an

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[6] Emerging pollutants, or *pollutants of emerging concern*, are substances of diverse origin and chemical nature that are present in the environment but are not routinely monitored or regulated, which have the potential to adversely affect human health and the environment They include personal care or household cleaning products, pesticides, industrial additives, among others.

increasing health risk. Climate change could also induce changes in the behavior of the population, for example, the time that individuals remain indoors, as well as modify the availability and distribution of allergens derived from plants and fungi, this will have effects on asthma and allergic rhinitis in children and adults; consequently, policy adjustments and lifestyle changes will need to be addressed to mitigate these deleterious effects.

When estimating future health effect, in addition to uncertainty in the concentrations of O_3 and PM, there are uncertainties in risk estimates, such as the modification of the effect by temperature in the relationship between pollutants and the human response to the pollutants, altering possible future adaptation resulting from these changes and a potential new risk associated with exposure (see for example, Kinney, 2018; Doherty et al., 2017). It is necessary to begin evaluating the implications of climate change on human health and orient policies towards the mitigation of climate change and air pollution, thus enhancing the health benefits and optimizing resources and costs.

- ***Health surveillance system.*** An interesting proposal is to design and implement a health surveillance system in conjunction with existing environmental monitoring networks in the Megalopolis. The integration of the systems could substantially help the early identification of actions to mitigate exposure to air pollutants, including extraordinary events such as those presented during the COVID-19 pandemic. Furthermore, the proposed integration may help improve the evaluation of the effectiveness of air quality control programs.

- ***Chemical composition of the particulate material and emerging toxins***. The associations between the health impacts and the toxicity of the different chemical speciation in the particulate matter should continue and increase, especially for the components of PAHs, metals, and black and organic carbon. This will allow us to understand how chemical aggregation and aerosol formation determine the molecular activation of pathophysiological processes of acute and chronic diseases. It is also necessary to carry out studies of emerging toxic particles, such as ultrafine particles, microplastic particles and those that do not derive from combustion such as brake and tire wear, identifying their emission sources and toxic potential.

- ***Methods of health studies***. To help in the development of policies to improve air quality, it is necessary to integrate the results of different methods of epidemiological studies such as ecological, case series, cross-sectional studies, case controls, cohort studies, and interventions. For health studies, *in vitro* and *in vivo* models of exposure to toxicants, high-throughput molecular techniques, and physiological function parameters of chronic diseases must also be integrated. It is necessary to advance in the study of the synergistic effects of the urban mix, as well as the effects of emerging pollutants. Exposure models used in epidemiological studies can benefit from the use of data obtained from satellite platforms and low-cost technologies, as well as from the output of numerical model ensembles.

- ***Data on criteria pollutants and other species of interest.*** Data for criteria pollutants with adequate spatial and temporal coverages and resolutions are required for epidemiological and exposure studies. It is necessary to increase the quality of the data to reduce the uncertainty in the evaluations of the impacts. Evaluation of the impacts of emerging pollutants will require the implementation of new technologies in the monitoring networks or in carrying out field campaigns.

- ***Development of management indicators based on the improvement of public health***. Air quality management could benefit from the development and incorporation of health-based indicators that could relate changes in disease incidence or attributed mortality to changes in levels of pollutants such as O_3 and $PM_{2.5}$.

Knowledge gaps:

- In the Mexican context, is there new scientific information on the health effects related to air pollution? What has been the recent information on air pollution and health?
- Is there evidence of chronic and acute effects aggravated by exposure to poor air quality?
- Is there evidence of synergistic effects related to exposure to the various mixtures of pollutants found in different urban environments? Is there sufficient data for its evaluation?
- Is it necessary to develop concentration-response functions suitable for the Mexican population?
- What are the social and economic costs associated with air pollution? Is it necessary to develop methodologies to support cost-benefit evaluations in the entities of the Megalopolis?
- What have been the advances to better estimate the health effects of air quality quantitatively?
- What is the contribution of outdoor ambient air pollution to indoor exposure?
- What are the thresholds for exposure to particulate and gaseous pollutants? What would be the challenges to achieve them?
- Is it necessary to include any other pollutant or pollutants (for example, ultrafine particles, PAHs) within the ambient air quality regulations?
- How will climate change modify the impact on health?

CHAPTER 6. AIR QUALITY MANAGEMENT PROGRAMS IN THE MEGALOPOLIS

6.1. Air quality management process and the role of scientific research

Air quality management refers to all the activities that a regulatory authority undertakes to help protect public health and the environment from the harmful effects of air pollution. It is an iterative and dynamic process represented as a cycle of inter-related elements, as shown in Figure 6.1 (NRC, 2004; Bachman, 2007). Typically, the process starts with a government institution defining air quality objectives, goals, and standards that establish threshold concentrations for key polluting species to protect public health and the environment. Air quality managers will need to determine the emission reductions required to meet the standards and goals. To better understand the challenge of air pollution, they apply various assessment tools, including emission inventories, air quality monitoring and modeling.

When developing the control strategies, air quality managers should include a timeline for compliance and implementation plans. To successfully achieve the required reductions, managers must implement the programs and enforce the rules and regulations. It is important to maintain a continuous evaluation to assess the effectiveness of the strategies and measure the progress towards meeting the air quality goals. Furthermore, because air quality management contains substantial scientific, technological, and societal uncertainties, it is necessary to continuously review and assess the objectives and the strategies as new information becomes available; for example, changes in emissions and meteorology that affect the area under control/surveillance. A precise definition of the problem may allow identification of new challenges to be solved to improve air quality. The management cycle is initiated again, incorporating the appropriate changes. In some cases, this might include setting new air quality standards. Throughout each stage of the process, it is essential to communicate with the public on the status of their air quality.

As shown in Figure 6.1, science and technology contribute to management through monitoring, analysis, research, and development, which provide the managers with the basis for making informed decisions. Importantly, successful air quality management will require decision makers to use the best available evidence, as well as data and information supported by the scientific and technological communities to achieve adequate and cost-effective reductions in pollutant emission.

Figure 6.1. Air quality management process. (Adapted from NRC, 2004 and J. Bachman, 2007).

In the US, the Clean Air Act (CAA, 1970) provides the legal framework, authorizing the US Environmental Protection Agency (US EPA) to set maximum allowable concentrations of six common air pollutants, ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2,), lead (Pb), and particulate matter (PM), by establishing National Ambient Air Quality Standards (NAAQS). Individual states then develop state implementation plans that show how, with the assistance of national control programs, they will meet these standards through the air quality management program (US EPA, 2022).

The Mexican government established the first ambient air quality standards (NOM, *Normal Oficial Mexicana*) for O_3, CO, NO_2, SO_2, Pb, and PM_{10} (particles with a diameter of 10 micrometers or less) in 1994 with the goal of protecting public health, following the example of the United States (DOF, 1994a, b, c). As described in Chapter 1, the standards are defined and issued by the Ministry of Health, which reviews them periodically; the current air quality standards are presented in Chapter 1, Table 1.1.

In Mexico, the federal government maintains a comprehensive approach to air quality management through the Air quality improvement programs (ProAire, *Programa Para Mejorar la Calidad del Aire),* which responds to the need of each one of the 32 states that make up the federation to have a preventive and/or corrective instrument in terms of air quality and health protection, as well as to comply with the applicable legal framework in this area. As of December 2022, all the states of the Megalopolis had a current ProAire, only Puebla's ProAire was in the process of updating (SEMARNAT, 2022).

Due to the high levels of air pollution in Mexico City and its metropolitan area, the Mexican authorities focused their first management activities on it. The government first recognized the existence of a severe environmental problem in the 1980s, when the new air quality monitoring network (RAMA, *Red Automática de Monitoreo Atmosférico*) revealed high concentrations of all criteria pollutants with O_3 peaking above 300 ppb 40–50 days per year. At that time, Mexico City was ranked as the most polluted megacity in the world (UNEP & WHO 1992). In the last three decades, air quality in the MCMA has been the subject of extensive air pollution control efforts. In addition, the combination of population, topography, meteorology, and the density of multi-pollutant emissions from the MCMA attracted the interest of scientific research, which promoted several large field measurement campaigns between 1995 and 2006, which provided a large amount of information on the emissions, dispersion and transformation of polluting species emitted to the MCMA's atmosphere and their urban, regional, and hemispheric impacts (Molina et al., 2019).

Section 6.2 describes the air quality management programs in the MCMA as an example to illustrate the process and evolution in the design and implementation of air quality improvement programs, as well as the role of science and technology in management. Section 6.3 describes the air quality management programs in the Megalopolis. Section 6.4 assesses some of the major programs of the MCMA and other entities of the Megalopolis to improve the air quality and the challenges involved.

6.2. Air quality management programs in the MCMA

During the 1990s, the Mexican federal government established several administrative agencies to address environmental issues, including the Metropolitan Environmental Commission (CAM, *Comisión Ambiental Metropolitana*) to coordinate the various levels of government dealing with metropolitan environmental issues, as well as a Metropolitan Environmental Trust Fund of the Valley of Mexico (*Fideicomiso Ambiental Metropolitana del Valle de México*) to support CAM projects by receiving money collected from the application of a tax surcharge on gasoline sold in the MCMA. Most of the Mexican air pollution control programs in the 1960s and 1970s targeted mainly the soot and smoke emitted from large industrial facilities. In the late 1980s and early 1990s, as the monitoring data showed increasing trends on both O_3 and particulate matter, strategies focused on reducing emissions of Pb, SO_2, CO, NO_X (nitrogen oxides), and PM. Among the sources of these compounds, the transportation sector and several large point sources stood out, such as refineries within the basin (Molina and Molina, 2002).

The first air quality management program, the Comprehensive Program Against Air Pollution in the MCMA (*Programa Integral contra la Contaminación del Aire* or PICCA), was implemented in 1990 (DDF, 1990) and six years later was replaced by the Program to Improve the Air Quality in the Valley of Mexico (*Programa Para Mejorar la Calidad del Aire en el Valle de México 1995–2000* or ProAire 1995–2000) in 1996 (DDF, 1996) In 2002, the 10-year air quality management program ProAire 2002–2010 was developed (CAM, 2002), and in 2010, ProAire 2011–2020, was enacted (CAM, 2011). In 2021, the new ProAire 2021-2030 was released (SEDEMA et al., 2021).

International collaboration

During the design of the air quality management programs, the MCMA benefited from the experience of Los Angeles in California by adopting emission control strategies and technologies, following the recognition of the smog problem in the 1950s by Haagen-Smit (1952). The actions included the introduction of unleaded gasoline and eventual elimination of lead in gasoline, three-way catalytic converters, stringent NO_x control for O_3 and $PM_{2.5}$ (particles with diameters of 2.5 micrometers and smaller), the availability of low-sulfur fuels, and the use of diesel particle filters introduced by the California Air Resources Board (https://ww2.arb.ca.gov/).

International environmental agencies and financial institutions, international and national academic institutions, and foreign governments also provided financial and technical support, including the US EPA, the World Bank, the Japanese International Cooperation Agency (JICA), the Western Governors Association (WGA), and the German International Cooperation Agency (GIZ).

Role of science in air quality management in the MCMA

The government of Mexico has a history of collaborating with national and international scientific and technical experts. In 2000, at the request of the Mexican authority to support the design of a new strategic plan for the following 10 years, the Integrated Program on Urban, Regional, and Global Air Pollution at the Massachusetts Institute of Technology (MIT) conducted a comprehensive assessment of the air quality in the MCMA, which provided the scientific foundation for the ProAire 2002–2010. This work was documented in the book by Molina and Molina (2002). One of the important recommendations of the assessment was the need to obtain more extensive experimental data, derived from field measurements to update and improve the MCMA emissions inventory and to improve the current knowledge of the chemistry, dispersion, and transport processes of the pollutants emitted to the MCMA atmosphere. These recommendations led to the MCMA-2002/2003 field measurement campaign sponsored by the CAM (Molina et al. 2007).

The scientific findings from MCMA 2002/2003 were instrumental in planning the MILAGRO campaign in March 2006 (Molina et al. 2010; Singh et al. 2009). The MCMA-2002/2003 and MILAGRO-2006 campaigns provided wide-ranging meteorological, gas, and aerosols measurements. Over 200 peer-reviewed publications resulted from both intensive campaigns. The review of these publications significantly improved our understanding of the meteorological and photochemical processes involved in the formation of O_3, secondary aerosols, and other pollutants, as well as their transport, transformation, and fate. The scientific findings from the field studies and the policy implications were incorporated by the Mexican government officials as the scientific basis in the design of Mexico's air quality management program, ProAire 2011-2020 (CAM, 2011).

After three decades of air quality management programs based on scientific, technical, social, and political considerations, the MCMA has made significant progress towards solving air pollution problems. The atmospheric concentrations of SO_2, CO, and Pb were drastically reduced, and currently are below the present air quality standards. Although O_3, PM_{10}, and $PM_{2.5}$ concentrations have also decreased significantly, they are still at levels that are far from meeting the respective air quality standards. Ambient concentrations of O_3 and $PM_{2.5}$ have stalled since 2010 and threaten to rise again (Velasco & Retama, 2017; Zavala et al., 2020).

Prior to the development of the new ProAire 2021-2030, SEDEMA, in coordination with the MCE2 and the Mexican Climate Initiative (ICM, *Iniciativa Climática de México*), held a workshop to evaluate the ProAire 2011-2020 and identify strategies to improve the air quality of Mexico City (SEDEMA, 2018a). The workshop was attended by national and international experts in air pollution science and policy. The workshop report emphasized the need to implement additional control measures, which would require substantial investments, particularly in the transportation sector, as well as strong political decisions by the federal government and the authorities of the governments of the State of Mexico and Mexico City.

The workshop made it clear that adequate air quality management must include analysis and evaluation of the following components of the air basin: a detailed inventory of pollutants from emissions sources, transport and dispersion modeling, atmospheric monitoring of pollutants and the determination of the spatial and temporal patterns of their concentrations, and the identification and evaluation of health impacts through exposure and epidemiological studies. Based on this technical-scientific information, it was recommended to formulate and implement regulations, standards, and public policies for the reduction of polluting emissions, which, together with adequate surveillance to guarantee their application and compliance, should lead to a progressive improvement in air quality. A successful result will be to arrive at integrated control strategies that are effectively implemented and accepted by the public.

The document with the results of the workshop (SEDEMA, 2018a) highlighted the importance of strengthening the collaboration between the states of the Megalopolis and with the corresponding municipal authorities, especially in air quality monitoring and the emissions inventory development (SEDEMA, 2018). The workshop confirmed that Mexico City had the best installed infrastructure and technical expertise in monitoring air quality in the region, as well as a robust emission inventory that was updated every two years; it was considered beneficial for the other entities of the Megalopolis to learn from the experience and best practices of SEDEMA. The findings and the recommendations from this workshop were incorporated in the new ProAire 2021-2030 (SEDEMA et al., 2021).

ProAire 2021-2030

The ProAire 2021-2030 of the MCMA includes 19 public policy measures, 40 actions and 127 activities aimed at preventing, controlling, and reducing emissions from priority sources, while addressing cross-cutting issues that strengthen air quality management, such as risk communication processes, citizen participation, institutional arrangements, monitoring, metropolitan coordination, and scientific research (SEDEMA et al., 2021).

The air quality management will focus on the following strategies:

1) Increase the use of cleaner technologies and strengthen regulations in the transportation sector.
2) Establish travel demand management to reduce number of trips, distances, and times.
3) Expand high capacity and low-emission transportation options.
4) Promote sustainable urban development.
5) Extend the use of cleaner fossil fuels (lower volatility and sulfur content) for the transportation and industrial sectors.
6) Modify regulations to reduce industrial emissions and apply surveillance schemes to control emissions from the steel, aluminum, glass, oil, and power generation industries.
7) Reduce the use of liquefied petroleum gas (LPG) and associated leaks at different stages of the supply chain.
8) Limit the VOC content in cosmetic and domestic products as well as those intended for industrial and commercial use.
9) Address the emission of fugitive particles from road traffic, agricultural activities, and wind erosion, through wet sweeping and road maintenance, good agricultural practices, and reforestation programs, respectively.
10) Improve the management of urban solid waste and wastewater.
11) Enhance the ability to fight forest fires.
12) Limit SO_2 pollution in the Tula-Vito-Apasco industrial corridor.
13) Promote healthy habits and awareness of air quality among the urban population to reduce their exposure and vulnerability to atmospheric pollutants.
14) Improve air quality monitoring in the MCMA.
15) Generate scientific knowledge to help improve air quality and public health policies.

According to SEDEMA, the estimated cost of implementing the ProAire will be about $377.35 billion Mexican pesos at 2021 prices. Successful implementation of the program is estimated to reduce between 20% and 25% of air pollution by 2030, including 20% of PM_{10}, 35% of $PM_{2.5}$, 35% of NO_X and 20% of VOC. This would result in the reduction of 4.3 $\mu g/m^3$ in $PM_{2.5}$, below the annual average concentration of 29.2 $\mu g/m^3$ in 2018, and could prevent 2,302 premature deaths, equivalent to an estimated economic valuation of $2,114 million pesos annually. Effective implementation of the air quality improvement strategies would be expected to achieve substantial health and economic benefits.

6.3. Air quality management in the Megalopolis

As previously discussed, through the implementation of the comprehensive air quality improvement programs (ProAire) based on scientific, technical, social, and political considerations, the Mexican authorities have made significant progress in improving the air quality of the MCMA. The air quality standards and the environmental contingency program were strengthened, recognizing the scientific evidence on health effects associated with exposure to increasingly lower concentrations of harmful pollutants. Nevertheless, concentrations of PM_{10}, $PM_{2.5}$, and O_3 are still above the respective air quality standards; substantial challenges remain to effectively reduce the concentrations of these pollutants.

Population growth, poorly planned urban expansion, intensive commercial and industrial activities, and high motorization of the metropolitan area and the surrounding Megalopolis region have exerted substantial changes in land use and mobility in the region, ultimately impacting the environment. Deficiencies in regional urban planning and differences in administrative and regulatory frameworks among the various government entities of the Megalopolis further contribute to the lack of an integrated sustainable development in the region, exacerbating the impacts on air quality and the environment in the Megalopolis (INECC, 2015).

In response to the environmental challenges of the urban conglomerate that is developing in the center of the country, which was designated as Megalopolis, the authorities of the six entities (Mexico City, State of Mexico, Morelos, Puebla, Tlaxcala, Hidalgo), in coordination with the Ministry of the Environment and Natural Resources (SEMARNAT), created the Environmental Commission of the Megalopolis (CAMe, *Comisión Ambiental de la Megalópolis*) in 2013 to plan and execute strategies for environmental protection, preservation and restoration of the ecological balance in the Megalopolis region (DOF, 2013). The CAM was replaced by CAMe, expanding the scope of activities to include the six neighboring states, to which Querétaro was later integrated. Information about the activities of CAMe is available on its website (https://www.gob.mx/comisionambiental).

One of the priorities of the CAMe has been to seek the harmonization and improvement of existing public environmental policies in each entity. In this respect, due to the episodes of high concentration of air pollutants that occurred in the first semester of 2016 in the MCMA, in August 2017, the Federal Management Program to Improve the Air Quality of the Megalopolis 2017 – 2030 (*Programa de Gestión Federal para Mejorar la Calidad del Aire en la Megalópolis 2017-2030*, o *ProAire de la Megalopólis* 2017-2030) was introduced (SEMARNAT, 2017b). This program contains six strategic lines and 38 actions to achieve the objective of improving air quality in the region of the Megalopolis, the implementation requires the committed participation of all the stakeholders involved, including the three levels of government (federal, state, and local), industry, academia, and the general public.

The strategic actions presented in the ProAire of the Megalopolis 2017-2030 aimed to reduce and control the main sources of atmospheric pollutant emissions in the Megalopolis, including O_3 precursor pollutants such as NOx and VOCs, as well as CO, CO_2, NH_3, SO_2, fine and coarse particles ($PM_{2.5}$ and PM_{10}) and black carbon (BC). In estimating the reductions, the ProAire used the year 2015 as the baseline to evaluate the results of the implementation of the strategies for the year 2030.

In recent years, several episodes of high O_3 concentrations have been recorded in Mexico City and in other entities of the Megalopolis. Because of the high non-linearity of the photochemical processes involved in O_3 formation, emission sources can have very different contributions in the formation of secondary atmospheric pollutants and it is difficult to assess the impacts of mitigation strategies. These contributions can be better understood using validated air quality models that take into account the diverse meteorological conditions, the chemical processes in the atmosphere, and the temporal, spatial and chemical distributions of emissions of O_3 precursors. Therefore, model-based studies of the physical and chemical processes that lead to high O_3 concentrations are an important step towards the design of emission control strategies aimed at reducing the health impacts of the population.

The LTM Center for Energy and the Environment (LTMCE2) carried out a modeling studies to estimate the impacts on O_3 concentrations resulting from the implementation of an integrated strategies for comprehensive emission control identified in the ProAire 2017-2030 for the Megalopolis (LTMCE2, 2017). In this study, three meteorological episodes were selected during high O_3 season (dry-hot season) in the Megalopolis. An integrated emission reduction scenario was designed that includes all the control strategies listed in the ProAire 2017-2030 for the Megalopolis, using the baseline emissions obtained for point, area, and on-road mobile sources for the Megalopolis and the State of Querétaro. The model-ready emission files were used to simulate the O_3 concentrations in the Megalopolis for both the baseline and the integrated emissions reduction scenario for the three selected meteorological episodes using the WRF-Chem air quality model.

The results suggested that the reductions included in the comprehensive emission control scenario affected the O_3 concentration levels with significant spatial variation. Substantial benefits from O_3 reduction were obtained in the northern and northeastern regions of Mexico City and in the cities of Toluca, Cuernavaca, Pachuca, and Querétaro, but negative impacts of O_3 in the central and southern regions of Mexico City and in the Puebla and Tula regions. These results were consistent for the three meteorological episodes selected. However, it is important to note that the evaluation of the impacts on air pollutant concentrations depended to a great extent on the accuracy of the emission inventories. Therefore, the report recommended field studies of O_3 precursors, as well as additional studies to evaluate the uncertainties in the emission inventories used for estimating the impacts of atmospheric pollutants in the region.

Ten months after the implementation of the ProAire 2017-2030, the CAMe reported on the publication of five Official Mexican Standards (NOM-016-CRE-2016, NOM-167-SEMARNAT-2017, NOM-044-SEMARNAT-2017, NOM-045-SEMARNAT-2017, NOM-004-ASEA-2017) to regulate emissions from mobile sources in circulation, encourage engine technology in heavy-duty vehicles, prevent the evaporation of hydrocarbons at service stations and guarantee the supply of ultra-low sulfur diesel in the industrial sector. In addition, more than 10,000 hectares of priority ecosystems were reforested and forest fires in the megalopolitan region have been reduced by 17%. This contribution to the region's air quality prevented the emission of 5 million tons of CO_2 into the atmosphere (SEMARNAT, 2018).

Nevertheless, there are still episodes of high pollution in the MCMA and the Megalopolis. One of the most severe pollution events occurred on May 14, 2019. A series of wildfires on the city's outskirts combined with stagnant weather conditions led to extremely high levels of $PM_{2.5}$. The CAMe declared an Extraordinary Environmental Contingency. In June 2019, CAMe introduced the following 14 measures to improve the air quality in response to the extraordinarily high pollution event (CAMe, 2019).

1) Reduction of emissions in the distribution and use of LPG.
2) Reduction of volatile organic compounds in coatings and household products.
3) Inspection and strategic surveillance for the control of emissions at gas stations.
4) Distribution of less volatile gasoline in the Megalopolis.
5) Best practices for fire management and fire prevention.
6) Control of emissions and use of clean fuels in the industrial sector.
7) Reduction of emissions due to urban maintenance.
8) Regulation of the circulation of freight transport and detection of ostensibly polluting vehicles.
9) Vehicle emissions standards: new regulations will set stricter emissions limits for new cars and provide incentives for the use of electric and hybrid vehicles.
10) Regulation of emissions of new motorcycles in the plant.
11) Implementation of a new scheme for the granting of vehicle verification holograms.
12) Promotion of sustainable mobility.
13) Increase the capacity of sustainable public transport.
14) Technological development to improve air quality.

Among the main measures were the reduction in the distribution and use of LPG, the improvement of gasoline quality and supervision at the stations. The provisions contemplated best practices for fire management and fire prevention with coordinated actions among all agencies. In the industrial sector, a control of emissions and use of clean fuels was proposed.

On May 6, 2022, another environmental contingency was declared due to the high concentrations of O_3 in the Valley of Mexico, Mexico City government authority convened a meeting with a group of scientists to discuss the recent pollution episodes. It was suggested that the increase in the number of contingencies in this O_3 season was likely due to a high-pressure system that stalled in the central region of the country, as well as the increase in temperatures due to climate change, a heat island and increased ultraviolet radiation, and the complex chemical reactions. An agreement from this meeting was that the ICAyCC of UNAM would coordinate a study to investigate the possible increase in VOC emissions that affect O_3 and the implementation of short-term measures, including reforestation program, heat island mitigation, and the impact of the intensive use of cleaning products during the recent pandemic period (La Jornada, 2022, Excelsior Digital, 2022).

The activation of atmospheric environmental contingencies is not exclusive to the MCMA, it also occurs in the other entities of the Megalopolis; therefore, in the context of magalopolitan coordination, the INECC carries out the project “Definition of thresholds and design of the general protocol of action of atmospheric environmental contingencies for the Megalopolis and evaluation of the cost-benefit of its application in the metropolitan area of Mexico City (*Definición de umbrales y diseño del protocolo general de actuación de contingencias ambientales atmosféricas para la megalópolis y evaluación del costo – beneficio de su aplicación en la zona metropolitana del valle de México (ZMVM)*) (INECC, 2023). The objective of this project is to develop a guide for the definition of the activation values of the different contingency phases for the criteria pollutants O_3, PM_{10}, $PM_{2.5}$, SO_2 and NO_2. Although the title refers to the MCMA, in reality it is intended as a document with application in the Megalopolis.

As illustrated in Figure 6.1, air quality management process is iterative, dynamic, and responsive to change. It is critical for CAMe to continue developing and implementing additional policy measures to improve the air quality in the MCMA and the other entities of the Megalopolis, supported by new scientific and technical information.

As indicated by the National Strategy for Air Quality Vision 2017-2030 (*Estrategia Nacional de Calidad del Aire Visión 2017-2030*) (SEMARNAT, 2017a), there is a need to generate reliable data and strengthen scientific and technological research to support and guide actions to improve air quality. The strategic line F of the ProAire 2017-2030 for the Megalopolis stated that the "*improvement of air quality management capabilities includes the preparation and development of a scientific research agenda and updating of air quality management tools*” (SEMARNAT, 2017b) Nevertheless, despite the importance of the actions described in both documents, there are no specific goals, no work plan or implementation strategy, and no mechanisms for monitoring and evaluation. Although efforts have been made to improve the air quality monitoring in several urban areas of the entities, there are no documented progress in terms of scientific research. Furthermore, when the research activities are carried out by government authorities, the measurement protocols and the data are usually not available to the scientific community, nor are the results subjected to peer review.

Finally, there is an important geographical disparity in the research work; the study of air pollution is scarce or non-existent outside of Mexico City. Despite the recent urban expansion and development beyond the periphery of the MCMA, some urban centers have significant levels of industrialization or evident problems of air pollution, there are few specialists and research centers dedicated to atmospheric sciences and health studies. As already mentioned above, there is an urgent need to strengthen the collaboration among the six states of the Megalopolis, including collaborative scientific research and field measurement studies. Furthermore, it will be beneficial for the other entities of the Megalopolis to learn from the experience and best practices of SEDEMA in atmospheric monitoring and emissions inventory development.

6.4. Assessment of major air quality programs

6.4.1. Integrated transportation-land use–air quality management in the Megalopolis

As in many large urban centers around the world, transportation is a major source of air pollution in the MCMA and in the Megalopolis region, but it is also a critical enabler of economic activity and beneficial social interactions. Transportation services are necessary to move goods and services, and to improve access to work, education, and other activities. As cities grow in population, area, and wealth, their transportation systems become more complex, with more people and goods traveling greater distances to more dispersed origins and destinations. This complexity gives rise to environmental, financial, and social constraints that often inhibit transportation system development. Furthermore, as populations increase and activities spread, additional issues arise from the need for multi-institutional, multi-jurisdictional, and multi-governmental coordination for system planning, development, operations, and management.

The government of Mexico City continues to strengthen the vehicular emissions control with advanced technologies and surveillance programs, remote sensors to identify high-emitting or non-compliance vehicles, fuel quality monitoring for both diesel and gasoline, improving public transportation (Metrobús), equipping buses with newer diesel technologies, introducing hybrid and electric taxis, improving mobility through bike-sharing program (Ecobici), and improving pedestrian areas. Nevertheless, according to the 2018 emissions inventory (SEDEMA, 2021), vehicles continue to be the main source of polluting emissions into the atmosphere with contributions of 94.6, 85.8, 43.0, 39.6, 34.5 and 22.2% for CO, NO_X, $PM_{2.5}$, PM_{10}, SO_2 and VOC, respectively (see Figure 3.1 in Chapter 3).

As noted in the comprehensive assessment of the MCMA transportation system by Gakenheimer et al. (2002), the challenge facing large urban centers such as the MCMA is to realize the benefits that transportation can provide without incurring the negative impacts that can also result from the "vicious cycle" of urban transport, including air pollution, congestion, accidents, noise pollution, and security. This dilemma becomes even more pressing under conditions of rapid urban growth in the State of Mexico and the nearby cities of Puebla, Tlaxcala, Cuernavaca, Toluca, and Pachuca, which increase travel demand significantly.

As the population has increased and the residential areas have decentralized, patterns of passenger trip mode choice in the Megalopolis have also shifted drastically. The number of private automobiles has increased significantly, largely because the existing transportation system has not adequately adapted to the changing demographic spatial distribution, resulting in new travel patterns due to inadequate strategic urban planning, the areas for living, working, and other activities are dispersed and disconnected. The result is an increase in the number of trips from the periphery to the urban center, and vice versa, leading to worsening congestion, increased risks of accidents, and localized emissions of toxic pollutants and greenhouse gases.

The following sub-sections describe some of the factors that contribute to transport-related emissions and the impact on mobility.

Evolution of size and composition of vehicle fleet

In 2020, in the seven states that make up the Megalopolis, the population increased by 1.3 times compared to 2000, while the vehicle fleet (18.8 millions) grew 3.6 times in the same period. This implies that the vehicle fleet has grown ten times more than the population in the last two decades in the Megalopolis, with automobiles, passenger transport, merchandise transport, and motorcycles increased by 256%, 159%, 146%, and 2087%, respectively (Lomeli Covarrubias, 2022). In addition to the growing motorization rate, commuters have shifted from high-occupancy modes of transport (for example, buses and subway) to medium- and low-occupancy transportation vehicles (*colectivos*) and private cars, as shown in Table 6.1.

In the MCMA, despite the strengthening of public transport and the promotion of personal mobility, the vehicle fleet continues a positive growth rate throughout the metropolitan area, dominated by private vehicles (see Figure 6.2). As can be seen in Figure 6.2a, the evolution of the vehicle fleet in the MCMA maintains a growing trend, mainly determined by the sustained increase in the fleet for private use (Figure 6.2b). In recent years, the growth rate in the metropolitan municipalities of the State of Mexico has been higher than in Mexico City. On the other hand, there is a significant disparity in the age of the vehicles, according to the emissions inventory for 2018 (SEDEMA, 2021), the average age of the fleet in the metropolitan area was 8.2 years for gasoline vehicles and 10.1 years for the diesel fleet. The average age of the vehicle fleet in Mexico City was 6.4 and 7.7 years, for gasoline and diesel vehicles, respectively. Although most vehicles have some advanced technology to reduce emissions, the benefits in their control could be outweighed by vehicle fleet growth, decreased traffic speeds and increased travel times and distances.

It is important to assess the rate at which older vehicles are removed from the fleet in the MCMA. According to a study conducted by Zavala et al. (2009) on the impacts of changes in gasoline-powered vehicle fleet characteristics between 2000 and 2006 on the concentration trends of pollutants, they observed that despite the increase in the size of the vehicle fleet during this period, the early morning ambient concentrations of CO and NO_X did not increase accordingly, likely due to the reported low removal rates of older vehicles, which do not have emissions control technologies, and in part due to the much lower emissions from newer gasoline vehicles. This study suggests that an emission-based air quality improvement strategy targeting large reductions of emissions from mobile sources should be directed towards a significant increase of the removal rate of older, highly-polluting vehicles. This is even more important for the on-road and off-road diesel vehicle fleets (Zavala et al., 2017a, 2017b). In addition to strengthening the emissions standards, it is important to provide incentives for cleaner and more efficient vehicles.

As riders seek alternative transportation options to offset congestion issues, the motorcycle fleet in Mexico has increased significantly in recent years (see Figure 6.2c). Motorcycles in Mexico have 4-stroke engines and can also be proportionally high emitters of toxics, CO, VOCs, PM, and other pollutants, since these vehicles do not have technologies installed for after-treatment of emissions. More importantly, there is currently no inspection and maintenance infrastructure to verify the emissions from motorcycles in Mexico.

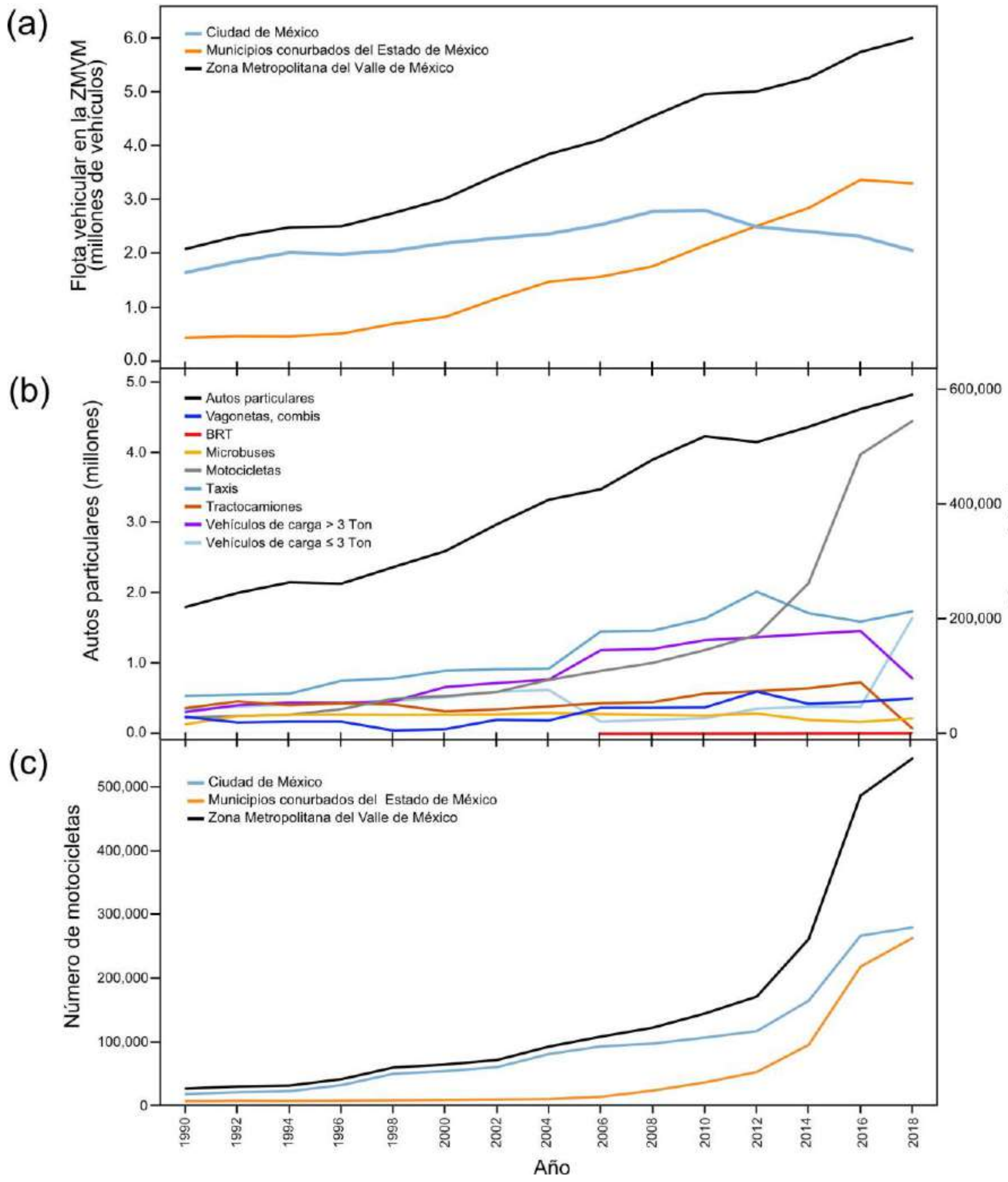

Figure 6.2. (a) Evolution of the vehicle fleet in the MCMA broken down by federal entity; (b) composition of the vehicle fleet of the MCMA; and (c) growth of the motorcycle fleet in the MCMA broken down by state (Own elaboration based on data from SEDEMA emissions inventories for 2018).

The increase in the number of motorcycles in circulation, not only as a means of transportation but also for providing courier and merchandise delivery services, was encouraged during the COVID-19 pandemic. According to INEGI data, in 2020 motorcycles represented 20% of vehicles registered in the city.[1] As discussed below (under "Hoy No Circular"), CAMe proposes regulations focused on new motorcycles, including promoting the use of electric motorcycles.

Vehicle technology and fuel quality

The modernization of the vehicle fleet in the MCMA started in the 1990s with the introduction of catalytic converters in new vehicles, the distribution of unleaded gasoline, and the implementation of stricter emission limits. In addition, gasoline was reformulated to limit the content of reactive compounds (olefins and aromatics), to lower evaporative emissions (vapor pressure reduction), and to allow a minimum oxygen content (oxygenate requirement), aiming to reduce the potential formation of O_3 and other oxidants, as well as the emission of air toxics such as benzene.

Substantial investments in refinery modernization have been made to lower the sulfur content of gasoline and diesel distributed in the MCMA. For some years now, these fuels have met standards that are comparable with low emission urban quality fuels in the United States and Europe with a maximum allowable sulfur content of 20 ppm (w/w) for gasoline and 15 ppm (w/w) for diesel. However, except in the main metropolitan areas (MCMA, Monterrey, Guadalajara), the main industrial corridors and the US–Mexico border regions, the rest of the country used diesel with high sulfur content with a maximum allowable of 500 ppm (NOM-016-CRE-2016) (DOF 2016). According to the NOM, ultra-low sulfur diesel should be distributed throughout the country by 2019. A document prepared by INECC (2019) indicated that this type of fuel was already marketed in most of the country in 2019, including the CAMe states; however, until now there is no official confirmation.

In an effort to reduce the VOCs emissions in the Megalopolis, from March to August 2020 and also for the same period in 2021, *Petroleos Mexicanos – Transformación Industrial* (PEMEX-TRI) changed the distribution of gasoline in the storage and distribution terminals located in Puebla, Puebla; Tlaxcala, Tlaxcala; Cuernavaca and Cuautla, Morelos; Toluca and San Juan Ixhuatepec, State of Mexico; and Pachuca, Hidalgo; to comply with the supply of gasoline with a Reid vapor pressure (RVP) of a maximum of 62 kPa, corresponding to volatility class A (CAMe, 2022a). This measure was added to the one in force in the MCMA where gasoline with a volatility class AA (RVP of a maximum of 54 kPa) is distributed throughout the year.

Currently, CAMe is promoting electric mobility *(movilidad eléctrica)* in the use of motorcycles, cars, vans, buses, and passenger and cargo transportation vehicles, which could improve air quality in the Megalopolis. However, the challenge is the initial acquisition cost of electric vehicles (CAMe, 2022b). Mexico City has a fleet of 493 electric vehicles, of which 483 are trolleybuses and 10 articulated buses (Metrobús) (E-BUS RADAR, n.d.).

Sustainable mobility plans in workplaces and schools

According to the most recent Origin-Destination Survey in the MCMA (INEGI, 2017), of the 34.56 million trips made on a weekday by the population aged 6 and over, 44% of trips are for work,

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[1] INEGI-Instituto Nacional de Estadística Geografía e Informática (s.f.). Vehículos de motor registrados en circulación, https://www.inegi.org.mx/sistemas/olap/proyectos/bd/continuas/transporte/vehiculos.asp, accessed on July 22, 2022.

24% for study, 13% for drop off and pick up, and 13% for shopping. Comparison of the distribution of trips by purpose from 2007 and 2017 shows similar pattern, with a slight increase in the proportion of trips made for work. Table 6.1 shows the mode share of these trips for the MCMA, Mexico City and the 59 contiguous municipalities of the State of Mexico and Tizayuca, Hidalgo.

Table 6.1. Trips made on a weekday by the population, by type and mode of transport used in at least one of its sections according to the geographical area of origin of the trip.

	MCMA: 34.56 million trips		**CDMX: 7.30 million trips**		**Contiguous municipalities: 17.09 million trips**	
	Million trips	%	Million trips	%	Million trips	%
Walking	11.15	32.23%	4.50	26.0%	6.62	38.74%
Public transport	15.57	45.00%	8.62	49.8%	6.88	40.26%
Private transport	7.29	21.07%	4.06	23.5%	3.17	18.55%
Bicycle	0.72	2.08%	0.24	1.39%	0.48	2.81%
Others	0.04	0.12%	0.02	0.12%	0.02	0.12%
Public transport: 15.57 million trips						
	MCMA		**CDMX**		**Contiguous municipalities**	
Microbús (colectivos)	74.1%		67.8%		82.1%	
Metro	28.7%		38.2%		16.8%	
Taxi	10.5%		11.2%		9.7%	
Metrobús o Mexibús	7.1%		8.8%		5.1%	
Autobus suburban	5.8%		5.3%		6.3%	
Autobus RTP o M1	2.6%		4.0%		0.9%	
Mototaxi	1.7%		1.1%		2.6%	
Others	3.5%		4.1%		2.7%	
Private transport: 7.29 million trips						
	MCMA		**CDMX**		**Contiguous municipalities**	
Car or truck	90.6%		92.7%		87.9%	
Motorcycles	5.1%		3.7%		6.9%	
Personal transport	4.4%		3.6%		5.3%	

Source: INEGI. Encuesta Origen -Destino en Hogares de la Zona Metropolitana del Valle de México (EOD) 2017 (accessed October 2022).

The results of the MCMA origin-destination survey show that most of the trips made are related to work and study. Furthermore, of the 15.57 million trips on public transport in the MCMA, three out of four use *Colectivo*; the Metro ranks second in frequency of use. Regarding private transportation, the use of motorcycle has increased exponentially in recent years as commuters look for alternative transportation options to increase mobility. In general, the use of higher-occupancy modes should be encouraged. It is particularly important to promote the use of public transit as a substitute for private car travel. To attract riders, public transportation needs to be improved.

The CAMe, together with the Interdisciplinary Center for Research and Studies on Environment and Development (CIIEMAD) of the *Instituto Politécnico Nacional* (IPN) and the Program for Advanced Studies in Sustainable Development (LEAD-Mexico) of *El Colegio de México* (COLMEX) organized a virtual seminar on "Good practices for sustainable mobility plans in workplaces and schools (*Buenas prácticas para planes de movilidad sustentable en lugares de trabajo y escuelas)*" with the aim of sharing experiences on how to reduce car trips to work and schools. The discussion highlighted strategies such as active mobility, sustainable mobility plans in organizations, the use of public and personnel transportation, as well as teleworking (*teletrabajo*) (CAMe, 2022c).

During the COVID-19 lockdown, many activities, such as work and education, were carried out through electronic means, and others used the flexible hybrid working arrangement (face-to-face and remote through videoconferences, email, and telecommunications). A decrease of up to 70% in vehicular traffic was observed compared to pre-pandemic levels in the MCMA (Figure 4.13 in Chapter 4). The reduction in motorization and other activities led to a reduction in the concentrations of some criteria pollutants as recorded in the air quality monitoring stations, as well as CO_2.

The pandemic lockdown offered a unique opportunity to experience teleworking on a larger scale. According to the CDMX Secretariat of Mobility, as part of the management of travel demand in CDMX, around 35% of work can be carried out remotely and the sectors most compatible with teleworking are: professional, technical, and scientific services; business and corporate administrative staff; financial and educational. Flexible schedules can increase the social benefits of teleworking.

To improve the efficiency of the transport systems and reduce transport-related emissions, regional coordination is necessary that integrates transportation network, urban planning, urban mobility, and air quality management. Cooperation between federal and local agencies responsible for environment, transportation, health, urban development, and public works is needed, as is public participation, leading to less reliance on individual vehicles through better provision of public transport and measures that allow for more journeys to be taken on foot or by bicycle. Furthermore, it is essential to develop metropolitan public transport policies and infrastructure that link sufficient and efficient routes to the municipalities surrounding Mexico City, where a significant number of long-distance trips originate.

Obligatory Vehicle Verification Program (PVVO)

The obligatory vehicle verification program (*Programa Verificación Obligatoria de Vehículos*, PVVO) was first applied in the MCMA starting in 1988, with the objective of reducing vehicle emissions by mandatory inspection of the environmental performance of the fleet and ensuring its proper maintenance. The program mandates that the emissions of each vehicle circulating in the

MCMA must be inspected every six months (Gakenheimer et al., 2002; SEDEMA, 2022a). The program has been combined with the "No Driving Day" (*Hoy No Circula*) program (see below), depending on the model year and the emission levels, the vehicles can obtain different exemptions, thus encouraging fleet renewal. The PVVO adopted the acceleration simulation mode (ASM) emissions testing and included tailpipe measurements of NO_X emissions. Starting in 2011, a major technological upgrade was implemented to improve the testing performance and minimize the chances of manipulation of test results by technicians. Starting in 2016, the OBD (on-board diagnostics) emission test was included as part of the tests for new vehicles (CDMX, 2019).

The maximum permissible emission limits have been strengthened several times and new testing instruments have been added to improve measurement capabilities, such as dynamometers for dynamic calibration and equipment for measuring pollutant emissions , as well as taking advantage of the on-board diagnostic system. The NOM-167-SEMARNAT-2017, "which establishes the maximum permissible limits of polluting emissions for motor vehicles circulating in Mexico City, the State of Mexico, Morelos, Puebla and Tlaxcala; the test methods for the evaluation of said limits and the specifications of information technologies and holograms" (DOF, 2017), and which is the reference for the PVVO, is currently under review. Future updates are expected to include changes to the specifications for vehicles powered by petroleum-derived fuels, alternative fuels, and hybrid vehicles.

No Driving Day (Hoy No Circula)

The "No Driving Day" (*Hoy No Circula* or HNC) program has its roots in 1987 as a citizen initiative of voluntary participation to avoid using the car once a week (see Appendix B of Molina and Molina, 2002). The program became mandatory in 1989 as part of a short-term emergency program for the winter months. Based on the last digit of the license plate, around 20% of all private vehicles were banned to circulate one weekday per week between 05:00 and 22:00, with the aim of reducing pollution, vehicular traffic, and fuel consumption. The HNC program became permanent in 1990 and was linked to the PVVO. In 1991, taxis and public transport vehicles were included in the HNC program. In 1992, vehicles using CNG or LPG were excluded from the circulation restrictions (Molina et al., 2019).

An undesirable consequence of the obligatory nature of the HNC was that families purchased an additional vehicle, usually older, which increased the vehicular fleet during the first years of the program. The acquisition of another vehicle and its characteristics depended on the family economic situation. Despite this, a dramatic reduction in traffic-related pollution was observed in the following years promoted by technological controls of exhaust emissions and improved vehicle maintenance.

To make the HNC program more efficient, significant modifications have been made to the circulation restriction and related policies. In 1997, a sticker code ("hologram") was used to identify the emissions level using the number "0" for low-emitting vehicle, and "1" and "2" for high emitters. The vehicles equipped with three-way catalytic converter complying with tighter emission standards were recognized with a "Zero" ("0") hologram sticker and were exempt from the driving ban. In 1999, new vehicles meeting even stricter emissions limits were issued a "Double Zero" ("00") hologram, exempting them from driving restrictions and emissions inspections during the first two years. Vehicles identified with a "2" hologram were included in the driving ban one day a week during weekdays and additional restrictions during contingency alert. A natural consequence of these actions was the gradual renewal of the vehicle fleet, with positive impacts on air quality despite vehicular growth.

The HNC program has undergone further changes in recent years, generally towards increasing circulation restrictions for older and polluting vehicles during weekdays and Saturdays. During 2007, the hologram “1” was removed from the program and in 2008, the circulation of vehicles not registered within the MCMA were prohibited between 05:00 and 11:00. In 2014, electric and hybrid vehicles received the hologram “0”, exempting them from any driving restriction. Hologram “1” was resumed in the program but vehicles were banned to circulate one weekday per week and two Saturdays per month, while those with hologram “2” were prohibited from driving one weekday per week and on all Saturdays. Recently, vehicles not registered in the entities of the Megalopolis not only have morning circulation restrictions, but they are prohibited one weekday per week and one Saturday per month (Molina et al., 2019).

In July 2015, there was a controversial decision by the Mexican Supreme Court of Justice that removed the vehicle age requirement to obtain the “0” hologram and exempted any vehicle from driving restrictions if it complied with the emissions limit. An immediate consequence of this court decision was the increase in the number of vehicles in circulation, leading to an increase in mobile emissions (Velasco and Retama, 2017). In 2016, after an extreme O_3 episode during March, the environmental authorities implemented changes in the program and mandated the installation of on-board diagnostics (OBD II) system in addition to exhaust emissions and visual inspection tests. The lack of OBD II in older vehicles prevented them from complying with the new requirements for the “0” hologram, reversing to some extent the impact of the previous court decision on vehicle age requirements. In April of 2016, the HNC was temporarily modified in response to the extreme O_3 episode: all vehicles were banned from driving one weekday per week and one Saturday per month during Phase I Contingency, in addition to the regular restrictions. Starting in June 2016, OBD II checking became part of the regular PVVO testing.

In March 2019, the CAMe announced some changes to the program (CAMe, 2019). In 2020, all electric and hybrid vehicles were exempted from driving restrictions. The “00” hologram was granted twice to new vehicles with a performance (expressed in terms of the number of kilometers traveled per liter of gasoline consumed, km L^{-1}) equal to or greater than 16 km L^{-1} and once to new vehicles with a performance equal to or greater than 13.5 km L^{-1} and less than 16 km L^{-1}. The “0” hologram was granted to vehicles complying with the OBD II, exhaust emissions, and visual inspection tests. A draft standard is being prepared to establish maximum permissible limits for the emission of pollutants into the atmosphere from the exhaust of motorcycles equipped with combustion engines.

In conclusion, the HNC program has evolved over the years with a major shift in primary objective from a driving ban to a vehicle fleet renewal initiative by coupling with the PVVO Program and providing strong incentives. The removal of older and more polluted vehicles from circulation should help in reducing vehicle emissions. However, despite the relative success of both programs (HNC and PVVO) during previous years, given the increase in the number of vehicles in the Megalopolis and specifically in the MCMA, there could be a gradual attenuation of the benefits. On the other hand, the program is not exempt from other imponderables such as fraudulent practices, the judicialization of some actions and new technological challenges (Ugalde, 2020). It is known that, despite advances in vehicular verification systems and surveillance in verification centers, corruption problems persist in the granting of holograms (Oliva, 2015), where the sophistication in fraudulent practices moves along with technological innovations. The above forces environmental authorities to maintain a permanent review of the program, continually incorporating technologies, instruments, modalities, monitoring systems and innovative solutions, to maintain the validity and effectiveness of the program. However, the implementation and standardization of new and best practices at the Megalopolis level presents additional challenges due to the disparity in the economic and technical capacities of the different entities. Currently, the *Centro Mario Molina* (CMM) with the support of the *Instituto Mexicano del Petróleo* (IMP) develops the project "Comprehensive Evaluation of the Federal and Local PVVO of the Megalopolis (*Evaluación Integral a los PVVO Federal y Local de la Megalópolis*)," with the goals (1) to evaluate the PVVO databases; (2) evaluate the equipment, hardware and software used in the verification centers; (3) technical evaluation using on-board equipment technologies; (4) evaluation of the PVVO using remote sensing technologies; and (5) evaluation of the application of NOM-167-SEMARNAT-2017. The results of this study will be available in the second semester of 2023 (CAMe, 2022a).

Alternative fuels: compressed natural gas (CNG) and liquefied petroleum gas (LPG)

In the 1990s, environmental authorities encouraged the conversion of intensively used vehicles to LPG with certified equipment. They also promoted the use of CNG by introducing vehicles built to run on natural gas. To encourage the use of alternative fuels, the vehicles running on LPG and CNG were exempted from the HNC program. Subsequently, the government reviewed the compliance with the technical and administrative guidelines for LPG or CNG converted vehicles, to assign them a "0" hologram, allowing them to circulate every day of the week. More recently, the PVVO has set limits for assigning the holograms "0", "1" and "2" to vehicles using LPG or CNG. An important issue related to the use of CNG and LPG is the potential for increased fugitive emissions from such vehicles. Currently, less than 0.6% of the vehicle fleet run on LPG or CNG.

6.4.2. Emissions from domestic and informal sources

Volatile organic compound emissions from informal sources (for example, street food cooking vendors, auto-parts painting, and open-air auto repair shops) will need to be better characterized. Efforts to reduce VOC emissions from the transport and large industrial sectors have shifted the relative contribution of these emission sources to atmospheric loadings of VOC in urban areas, increasing the relative contribution of VOC emissions from area sources. Therefore, to continue improving air quality, regulatory efforts and technological changes should include control strategies to reduce key VOC compounds from formal and informal area sources, and to have a better understanding of the contribution of VOC from consumer products to atmospheric chemistry.

Recent studies have found that leakages in the gas storage and distribution systems of LPG and natural gas contribute to the high concentrations of methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) in the atmosphere of Mexico City (Velasco et al., 2007; Jaimes-Palomera et al., 2016). The most recent scientific evidence indicates that the hydrocarbons associated with LPG emissions (propane and butane) are the most abundant in the atmosphere, and despite having low reactivity, due to their abundance they play an important role in O_3 production (Zavala et al, 2020). The residential, commercial, service, and industrial sectors are the main consumers of both fuels. Estimates suggest that 57% of LPG in the MCMA is consumed in the residential sector for cooking and water heating, while over 93% of CNG is consumed by industries (SEDEMA 2021). Therefore, it is important to establish inspection and maintenance programs for industrial, commercial, and domestic facilities. As part of the air quality and climate action programs, the government of Mexico City is encouraging the use of solar heaters to reduce dependence on LPG (SEDEMA, 2022b).

6.4.3. Reduction of emissions in industries and services

In the MCMA there are more than 77,000 industrial establishments of which 1925 are subject to environmental regulation, either local or federal. The consumption of natural gas provides most of the energy required by the industrial plant, annually consuming 4.6×10^9 m^3. In general, the industry has a minor contribution to the emissions of the criteria pollutants, with the exception of SO_2, where they contribute around 33% of the total emissions (SEDEMA 2021). Currently, regulations to control emissions are well established for large industries, but this is not the case for the medium, small, and micro industries.

The partial substitution of fuel oil by natural gas in the two power plants in Mexico City and the use of low sulfur diesel in major industries around the MCMA have been successful in reducing SO_2 concentrations, as well as emissions of particles and their precursors. However, the large industrial Tula-Tepeji corridor, located about 70 km northwest of the center of Mexico City, continues as one of the main sources of SO_2 and particulate sulfate for the MCMA. The environmental authorities consider limiting the SO_2 emission from this region as an important goal of the ProAire 2021-2030. As noted in Section 4.3.5.1 of Chapter 4, CAMe has sponsored a short-term measurement study coordinated by INECC; however, at the time of preparation of this document, the results were not available (INECC, 2021).

The establishment of the environmental permits for industries of local jurisdiction (*Licencia Ambiental Única*, *LAU*) and for facilities of federal jurisdiction *(Cédula de Operación Anual, COA)* has been an important measure for improving the environmental management of industries. However, the emissions inventory shows that industries of local jurisdiction are still high emitters of NMVOCs (non-methane volatile organic compounds), while industries of federal jurisdiction are large emitters of $PM_{2.5}$, SO_2 and NO_x. Some of the NMVOCs emitted by industries are highly toxic and reactive. Furthermore, many industries are not included in the MCMA emissions inventory because they are not regulated and do not have reporting requirements. There is also confusion in classifying small but abundant industrial sources as some shops are classified as area sources.

Currently, the governments of the entities are working on the development of actions aimed at reducing the emissions from the industry of local jurisdiction. In the case of Mexico City, SEDEMA prepared a proposal for actions to reduce PM, VOC, and NO_X emissions through self-regulation.

6.4.4. The Program to Prevent and Respond to Atmospheric Environmental Contingencies

On May 29, 2019, the Program to Prevent and Respond to Atmospheric Environmental Contingencies (PPRECAA, *Programa para Prevenir y Responder a Contingencias Ambientales Atmosféricas*) came into force for its application in Mexico City and in the 59 municipalities of the State of Mexico that are part of the MCMA (Diario Oficial de la Ciudad de México, 2019). This program replaced the Atmospheric Environmental Contingency Program (PCAA, *Programa de Contingencias Ambientales Atmosféricas*) in operation since 1986.

The PCAA integrated a set of emergency enforcement measures in the event of a severe pollution episode and had two fundamental objectives: (1) alert the public about air pollution risk levels, and (2) implement actions to alleviate the pollution levels. Its activation occurred when the concentrations of O_3 or PM_{10} in the ambient air exceeded the thresholds established by the environmental authorities. The PCAA used data from measurements made by RAMA) for the hourly average of O_3, the 24-hour moving average of PM_{10}, as well as the weather forecast. The activation values were periodically updated in agreements between the environmental authorities of the federal and local governments involved in the CAM.

The PCAA began in 1986 with two activation phases, Phase I and Phase II. Phase II corresponded to a critical environmental emergency situation where the health of the entire population was compromised. The Phase I activation threshold was higher than the current standard value, but significantly less than the Phase II activation value. In 1996, a Pre-contingency stage was included, which was activated at levels lower than Phase I and was considered as a preventive alert stage with the main objective of informing and motivating voluntary action to avoid worsening air quality. Since 1986, the activation thresholds and actions have been updated periodically, adapting them to management progress or some extraordinary pollution situation, mainly to alleviate social pressure, as occurred in 2016 after a severe O_3 pollution episode or as the May 2019 case mentioned above (see Figure 6.3).

The PPRECAA maintains Phases I and II but the activation thresholds were updated, the Pre-contingency Phase was eliminated and replaced by the Preventive Phase, which is activated when the air quality forecast indicates a probability greater than 70% of reaching an O_3 concentration >140 points (>143 ppb) in the air quality index for the following day or when PM_{10} or $PM_{2.5}$ levels exceed 135 points (>172 or >81 $\mu g/m^3$, respectively) in the index for that day. With the inclusion of $PM_{2.5}$, the program implements a new protocol for the reduction of emissions of this pollutant and includes it in the Combined Phase, which in the PCAA considered only O_3 and PM_{10}.

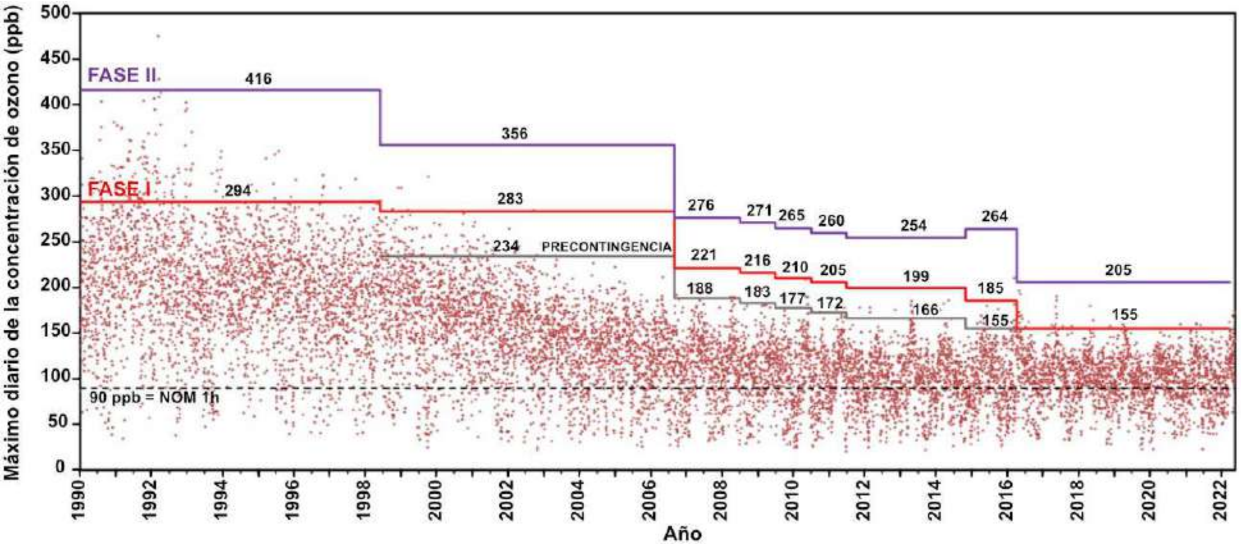

Figure 6.3. Daily maximum ozone concentrations (1990–2022) illustrating the changes on the threshold used to trigger environmental contingency (own elaboration with data from the SEDEMA Air Quality Monitoring Directorate).

Like the PCAA, the PPRECAA establishes the coordination mechanisms between the authorities of the federal governments, Mexico City, and the State of Mexico, as well as the actions to be implemented by the corresponding authorities, owners of industries, businesses, services, and citizens in general, with the purpose of preventing and controlling air pollutant emissions and reducing adverse effects on the population's health. Like the PCCA, this program is activated with inputs provided by RAMA, which include air quality data for O_3, PM_{10}, and $PM_{2.5}$, as well as meteorological and air quality. forecasts. During a pollution episode, CAMe is responsible for activating the PPRECAA.

Although it includes a preventive phase based on the numerical forecast, the PPRECAA continues to act as a corrective program to mitigate risks in the event of a pollution episode, similar to what happened with the PCAA. Since the mitigation actions are applied after the event occurs, it is ineffective in reducing the levels of the pollution that triggered the contingency. The impacts and benefits of the contingency alert are effective the next day by reducing the load of emissions into the atmosphere; however, its effectiveness could be minimal when the meteorological conditions continued to be favorable for photochemical activity and adverse for the dispersion of pollution. The Preventive Phase, which could have a precautionary impact, is rarely applied even when the conditions for it are present..

Up to now, the impact of the PCAA, and now the PPRECAA, in the mitigation of pollution levels and the protection of health during pollution episodes has not been scientifically evaluated, but it is a fact that the PPRECCA has an immediate positive consequence by maintaining a sense of urgency among the population in the face of health risks from air pollution. The application of Phase I or II of the PPRECAA has impacts on economic and productive activity; therefore, given the uncertainty in its performance, it is necessary to evaluate its effectiveness and carry out a cost-benefit analysis.

The effectiveness of forecast systems to anticipate a critical pollution event is an aspect that requires the attention of the environmental authorities, since, due to the deterministic nature of the numerical models and the limitations in the knowledge of atmospheric chemistry and physics, the systems could experience difficulties in anticipating with a reasonable margin of uncertainty some of the events that could occur during atypical situations of the atmosphere not represented by the model parameterizations. The Mexico City's Air Quality Forecast System has an acceptable performance for O_3, with certainty percentages of about 80% for the 24-hour and 48-hour forecasts (SEDEMA, 2018b). However, during contingency events, the model may not correctly predict some of the cases. The improvement of the model requires a case-by-case evaluation to analyze the conditions that motivated the event and identify the causes behind the poor performance and move towards the proposal of better parameterizations, but this process will require an extraordinary effort to obtain or generate the necessary data. At the Megalopolis level, the experience of Mexico City has been replicated in some urban areas; however, there are important limitations due to the lack of monitoring data and the absence of an adequate air quality forecasting system.

The National Institute of Public Health (INSP) and the INECC made a proposal for new activation levels of atmospheric contingencies based on literature review of environmental contingency programs in Mexico and in other parts of the world, local epidemiolocal studies, and the analysis of health effects for the MCMA. The main objective of this proposal is to provide the foundations for the design of a health-based contingency program, supported with technical and scientific elements for the analysis and definition of the concentrations of air pollutants to be considered in a new environmental contingency program. From the analysis of the daily data on the concentration of pollutants and health events carried out by INSP, it was found that the levels at which contingencies are currently decreed prevent a very limited number of health events, therefore they need to be adjusted. Furthermore, it is necessary to establish the threshold for other pollutants such as NO_2 and SO_2 (INSP, 2022)

The recent study for the "Definition of thresholds and design of the general protocol for atmospheric environmental contingencies action for the Megalopolis and cost - benefit evaluation of its application in the metropolitan area of the Valley of Mexico (*Definición de umbrales y diseño del protocolo general de actuación de contingencias ambientales atmosféricas para la megalópolis y evaluación del costo – beneficio de su aplicación en la zona metropolitana del valle de México*)" (INECC, 2023) proposes changes in the thresholds for the Preventive, Phase I and Phase II phases for O_3, $PM_{2.5}$ and PM_{10}; proposes thresholds for SO_2 and NO_2; adds a new phase to the program called the Seasonal Phase with permanent actions; and reviews transitional actions during Phases I and II. The proposals for O_3 and $PM_{2.5}$ are described below:

For O_3:

- A seasonal phase from March 15 to June 15 with restrictive measures in various activities, mainly in mobility.
- A preventive phase with a threshold of 0.135 ppm in at least three stations for at least two hours with information and dissemination actions.

- A Phase I with a threshold of 0.155 ppm, in at least three stations for at least two hours with restrictions on some activities that do not imply additional loads to those applied in the Seasonal Phase.
- A Phase II with a threshold of 0.175 ppm in at least two stations for at least two hours, with extraordinary restrictions on mobility and production, school and service activities.

For $PM_{2.5}$:

- A seasonal phase from December 1 to March 15 with restrictive measures in various activities that generate particles.
- A Phase I with a threshold of 71 µg/m^3 for the 24 hour moving average , during two consecutive hours in at least three of the stations suitable to activate the PCAA, includes additional restrictions to those of the seasonal phase.
- A Phase II with a threshold of 110 µg/m^3 for the 24-hour moving average, for two consecutive hours in at least two of the stations suitable to activate the PCAA, with extraordinary restrictions on mobility and production, school and service activities.

Considering the set of modifications proposed for all pollutants, their implementation could offer multiple challenges in different institutional, social and economic spheres, which could be magnified if the implementation is intended for the entire Megalopolis. It will be necessary to implement clear operating rules for each one of those involved, make the applicable regulatory changes or improvements, and improve monitoring and forecasting. One of the main limitations of the proposal has to do with the possibility that the economic impact of the application of the actions is greater than the expected benefits.

6.4.5. Climate change mitigation plans

Climate change and air quality are intricately connected by sources and impacts. It is important to integrate air quality and climate action plans into environmental policy design for potential synergistic benefits.

The government of Mexico, through SEMARNAT and INECC, has participated actively in international climate negotiations. Since signing the United Nations Framework Convention on Climate Change (UNFCCC), which was ratified by the Mexican Senate in December 1992, Mexico has presented six National Communications to UNFCCC. In 2012, Mexico joined the Climate and Clean Air Coalition (CCAC) to reduce Short-Lived Climate Pollutants (SLCP)[2] as a founding member. Subsequently, with the collaboration of MCE2, Mexico developed the pilot national planning for SLCP, which provided a strategic review of possible options to reduce SLCPs in Mexico (MCE2-INECC, 2013). Mexico submitted its NDC (Nationally Determined Contribution) as part of its commitment to the UNFCCC Conference of the Parties (COP21) held in Paris in December 2015, pledging to reduce greenhouse gases (GHG) and black carbon (BC) emissions. During the COP 26 in Glasgow, Scotland, in November 2021, Mexico joined over 100 countries in pledging to reduce CH_4 emissions by 30% by 2030 (UNEP, 2021). As noted in Section

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[2] Short-lived climate pollutants (SLCPs) are also known as short-lived climate forcers (SLCFs).

4.5 of Chapter 4, it is important to improve the estimates of CH_4 emissions, especially from the energy sector and the agriculture sources, to identify and implement effective mitigation policies.

In addition to reducing emissions of criteria pollutants and O_3 precursors, Mexico City aims to reduce emissions of GHG and short-lived climate pollutants (BC, CH_4, and some hydrofluorocarbons) through a series of air quality management programs and climate action plans developed and implemented in recent decades. These actions include strengthening emission control standards for vehicles, developing sustainable mobility plans in workplaces and schools, promoting electric mobility, promoting energy efficiency for public and private buildings, encouraging solar water heating, improving collection and disposal of solid waste, and using landfill gas recovery to supply clean energy (SEDEMA, 2022b).

Recently, the atmosphere of the MCMA and other entities of the Megalopolis has experienced progressive warming, possibly as a result of the synergistic interaction between increased anthropogenic warming, land cover modification, and changes in temperature associated with global climate change. Air quality is strongly dependent on climate and is therefore sensitive to climate change. Elevated temperatures from urban heat islands and climate change can affect the air quality as well as contribute to heat-related illnesses and discomfort. Thus, it is important to design and implement strategies to reduce the effects of urban heat islands, which in turn, can help mitigate climate change. Integrating air quality and climate stabilization goals into environmental policy design would be highly beneficial.

6.4.6. Cost-benefit analysis for implementing air quality management measures in the Megalopolis

Monetary valuation of the costs and benefits of pollution reduction is essential to guide management policies. Regulatory actions are usually restrictive and can have strong economic or social impacts. Therefore, this balance of costs is essential to economically justify government actions and interventions to the affected sectors and society in general.

As shown in Figure 6.1, in the development of strategies, the discussion centers around determining the appropriate level of emission reduction. In economic terms, the optimal level is found at the point where the cost of reducing emissions equals the benefits of the resulting reduction in damages. Identifying this optimum point requires assigning a monetary value to the reduction measures and the damage caused by pollution. The ideal scenario occurs when the costs derived from the benefits of reduction policies exceed the costs of implementation, facilitating the identification of the appropriate level of reduction and justifying its implementation to society (Lanigan, 1993).

Cost-benefit analysis provides an accounting of the actual costs and benefits of environmental policies by quantifying their effects. The costs associated with implementing environmental policies are often divided into three economic sectors: private sector costs, social costs, and government regulatory costs. The costs incurred by the private sector include direct and indirect costs. Direct costs include capital costs, such as expenses for facilities and equipment, and operating costs for the operation and maintenance of pollution control processes. Indirect costs stem from pollution control requirements, such as diverting capital to purchase and operate pollution control equipment. Social costs refer to lost income from other uses of a resource, because the resource was used to comply with environmental regulations. The costs for national and local regulatory agencies refer to the resources of the agency's budget allocated to the design, implementation, monitoring and supervision of environmental programs, including personnel, contracts, and financial assistance to regulated companies, which may include costs associated with the evaluation of impacts.

The valuation of environmental benefits can be done by using physical relationships that formally describe cause and effect relationships to obtain objective measures of the damage resulting from environmental change, assuming that individuals are willing to pay an amount less than or equal to the costs incurred as a result of the effect. The valuation can also be carried out using proxy market prices, based on the evaluation of the possible damages expressed or revealed in real or hypothetical market behavior (Voorhees et al., 2001).

Evaluation of health impacts in the Megalopolis

In recent years, several health impact assessments (EIS, *evaluación del impacto en la salud*) have been carried out in the Megalopolis region, however, the majority correspond to Mexico City and its metropolitan area, due to the greater availability of air quality monitoring data, population characteristics and morbidity and mortality records. Section 6.4 of ProAire 2021-2030 (SEDEMA et al., 2021) presents a complete summary of these studies. The results of two recent studies are described below.

The National Institute of Public Health quantified the number of premature deaths that could be avoided if the concentrations of the main air pollutants ($PM_{2.5}$, PM_{10} and O_3) were reduced in the municipalities of the entities that make up the Megalopolis (INECC, 2016). The study used the 2014 air quality data reported by the different monitoring systems in the region to estimate the base year, assigning a radius of 10 km to the spatial coverage of the monitoring stations. The concentration response functions (FCR, *funciones concentración respuesta*) were obtained from the international literature review. The EIS considered three reduction scenarios:

1) NOM limit values (annual means for $PM_{2.5}$: 12 µg/m^3 and PM_{10}: 40 µg/m^3, 8-hour average for O_3: 70 ppb),
2) WHO guideline values (annual means for $PM_{2.5}$: 10 µg/m^3 and PM_{10}: 20 µg/m^3, 8-hour average for O_3: 50 ppb), and
3) an intermediate scenario (annual means for $PM_{2.5}$: 11 µg/m^3, PM_{10}: 30 µg/m^3, 8-hour average for O_3: 60 ppb).

For clarification purposes only, the WHO guideline values were recently updated (2021), the values used in the studies described in this section used the previous WHO 2005 update. Table 1.1 in Chapter 1 list the current WHO guideline values and Mexico air quality standards.

In the economic assessment, the value of a statistical life (VVE, *valor de una vida estadística*) was used, which consists of calculating the willingness of individuals to pay to ensure a marginal decrease in the risk of premature death. Two estimators were used for VVE values, one based on previous local studies (VVE = $1.68 million pesos) and the other determined by transfer of benefits

(VVE = 13.85 million pesos) (Kochi et al., 2006; SEMARNAT&INECC, 2014, de Lima, 2019). Using the local VVE of $1.68 millon pesos in the evaluation of scenarios, the benefits of reducing $PM_{2.5}$ levels to the NOM and WHO levels yielded values for the number of deaths avoided of 8,464 and 9,767, respectively, which corresponds to an economic valuation of $14.3 and $16.5 billion pesos; in the average scenario the benefit would be $14.6 billion pesos. In the case of PM_{10}, the number of deaths prevented was 2,756 and 12,089, respectively, with an economic valuation of $4.7 and $20.4 billion pesos. In the intermediate scenario, 7,422 deaths would be avoided with a benefit of $12 billion pesos. Finally, for O_3, the number of deaths prevented was 260 and 1,089 for the NOM and WHO scenarios, respectively, with values of $0.4 and $1.8 million pesos. In the intermediate scenario, 674 premature deaths would be avoided with an economic benefit of one billion pesos. In all three scenarios, the highest number of deaths avoided was observed in the MCMA due to the higher population density and better monitoring coverage.

In 2020, SEDEMA, in collaboration with the INSP, estimated mortality attributable to assumed concentrations of $PM_{2.5}$ and O_3 in the MCMA considering four scenarios: (1) compliance with NOM limit values, (2) compliance with WHO guideline values, (3) 10% reduction in current levels, and (4) an ideal scenario with a value of 2.4 $\mu g/m^3$ for $PM_{2.5}$ and 38 ppb for O_3 (INSP & SEDEMA, 2020). The mortality estimate was made only for the population with monitoring representation; this is equivalent to 43% and 72% of the total population of the metropolitan area for $PM_{2.5}$ and O_3, respectively. The results indicated that if the NOM values and the WHO guideline values were met, 3539 and 4357 premature deaths, respectively, would be avoided. The scenario with a 10% reduction in current levels resulted in a decrease of 814 premature deaths, while the scenario with the best air quality would prevent 8983 deaths. Most of the deaths averted for each scenario was attributed to $PM_{2.5}$ reduction. An important caveat in this study was the limited spatial coverage of the monitoring, mainly in the contiguous municipalities in the State of Mexico, resulting in the underestimation of the calculated values. An economic valuation was not performed in this study. The main sources of uncertainty were associated with monitoring, population data, and the selection of concentration-response functions (FCR) used to estimate mortality.

Costs and benefits of the implementation of ProAire 2021-2030

As part of the preparation of ProAire 2021-2030, SEDEMA carried out a cost-benefit evaluation of the implementation of the program, considering the costs of its implementation and the expected health benefits (SEDEMA et al., 2021). The estimated cost for the implementation of ProAire is $280.71 billion pesos (at 2021 prices), this included the costs of implementing the 14 measures to reduce pollutants in the MCMA ($255.4 billion pesos), the costs of the measure corresponding to the Tula-Tepeji corridor ($24.4 billion pesos), as well as communication expenses, institutional follow-up, air quality monitoring and the research agenda ($965 million pesos). About 96% of the resources considered for the reduction of emissions correspond to the transportation sector.

The execution of all ProAire actions could reduce the annual average concentration of $PM_{2.5}$ by up to ~22% (equivalent to ~4 $\mu g/m^3$) relative to the scenario without the application of ProAire. For VOC and NO_X, the projected reduction would be 40 and 29%, respectively. In the case of O_3, the estimated reduction was ~2% (~3 ppb) in the annual average of the maximum daily values, this estimate would be within the uncertainty of the model. In a scenario with the application of ProAire, it was estimated that at least 6,000 deaths could be avoided in the year 2030, which is equivalent to an estimated value of 119,256 million pesos. These economic savings in 2030 would offset the implementation costs of the entire Program by more than 40%. It is important to mention that this cost-benefit assessment did not include impacts and benefits on morbidity, urban infrastructure, urban parks and conservation land..

Costs and benefits of the implementation of environmental contingencies

As part of the study "*Definition of thresholds and design of the general protocol for atmospheric environmental contingencies action for the Megalopolis and cost - benefit evaluation of its application in the metropolitan area of the Valley of Mexico (ZMVM)*" (INECC, 2023), an evaluation was carried out of the cost-benefit of the application of the Environmental Contingency Program (PCAA) using different values proposed for the threshold for O_3, PM_{10}, $PM_{2.5}$, NO_2 and SO_2, based on the limit values to avoid 5% of attributable mortality for each pollutant using 2019 as the base year. For example, in the case of O_3, a threshold value for activation of 136 ppb was proposed which, applied to the 2019 data, could prevent up to 181 deaths, equivalent to 5% of attributable deaths.

The evaluation was carried out for three scenarios with different VVE obtained from previous studies: $10 million pesos for a low scenario, $24 million and $66 million pesos for medium and high scenarios, respectively. The estimated benefit of the application of the PCAA for avoided deaths was $4,660 million pesos annually for the low scenario, $11,184 million pesos annually for the medium scenario, and $30,756 million pesos annually for the high scenario, the detailed analysis is shown in Table 6.2. In estimating the benefits, the costs related to morbidity were also considered. The results indicated that, when the high VVE was used, the benefit exceeded the costs of the actions by $271 million pesos; however, when the average VVE was used, the cost exceeded the benefit by $7,668 million pesos. In the low scenario, the costs of the actions were significantly higher than the benefit and therefore it was not considered. The study indicated that the value of the benefit could be underestimated by not including the costs of out-of-hospital treatment and for medical disabilities or parental care, or all diseases directly or indirectly related to the pollutants.

Table 6.2. Estimation of the annual economic benefits associated with 5% reduction in mortality attributable to pollutants in the MCMA (adapted from INECC, 2023).

			Expected annual economic benefits (in millons of pesos)		
Pollutant	**Threshold concentration value**	**5% annual reduction in attributable mortality**	**Low scenario**	**Medium scenario**	**High scenario**
O_3 (ppb)	136	181	1,810	4,344	11,946
PM_{10} (µg/m^3)	96	81	810	1,944	5,346
$PM_{2.5}$ (µg/m^3)	71	67	670	1,608	4,422
NO_2 (ppb)	86	119	1,190	2,856	7,854
SO_2 (ppb)	192	18	180	432	1,188
Total benefits	**---**	**---**	**4,660**	**11,184**	**30,756**

Considerations for the evaluation of the impacts of pollution in the Megalopolis

Valuing environmental costs is challenging and subject to uncertainties. The effects of air pollution on human health and productivity are the most susceptible to market valuation. While the effects on comfort (such as visibility, smell, and noise) are more susceptible to subjective evaluation. The health of ecosystems does not have a market value, nor can it be easily valued with surrogate market prices. Damage to property and non-living systems can be assigned a market-based value using a combination of a dose-response function followed by a damage function; however, they are often not quantified due to lack of appropriate dose-response functions. On the other hand, the costs related to the behavior of groups sensitive to pollution are difficult to quantify.

Due to the complexity involved in air pollution and its impacts, the assessments of impact generally establish assumptions to simplify the work, but these hardly reflect the real state of the problem, which considerably increases the uncertainty of the estimates.

Identification and assessment of pollution damage.

Damage attributable to air pollution may include damage to health, decreased agricultural yields, damage to buildings and historic heritage, and impacts on ecosystem. The type and extent of impacts are influenced by factors other than pollution, for example, health effects will critically depend on prior health and nutritional status, age, and access to medical services. There are other effects of air pollution that are more difficult to assess, such as impacts on infrastructure, agriculture, or ecosystems. These effects are scarcely considered in the cost-benefit evaluations of the entities of the Megalopolis. In most cases, this information is not available, difficult to collect, or it may be difficult to isolate the impact of air pollution from other influences.

The absence of data on the concentration of air pollutants or the availability of poor-quality data is a common problem in the region. The observations provided by atmospheric monitoring are necessary to assess the impacts of pollution. It will not be possible to estimate the real costs of environmental damage if the levels and variability of the pollutants are not known. The lack of adequate concentration-response functions (FCR) for the Mexican population is an important source of uncertainty in the evaluation of health impacts.

Another problem is the availability of methodologies to estimate the values that should be assigned to the different impacts of pollution. To monetize the impacts on health, the methods used in developed countries are generally used, however, their application faces the absence of the data necessary to make estimates. Sometimes the values obtained from other studies are used, but they may not be applicable for the region. For example, the impact on mortality requires the estimation of the VVE, which corresponds to people’s willingness to pay for environmental improvements or to accept compensation for the effects. The VVE could be overestimated when it is transferred from the values used by the developed countries, or could be underestimated when people tend to be less aware of the effects of pollution-related damage, or when there is insufficient information to value environmental benefits. In another example, when wages lost due to pollution-related illnesses are used as an indicator of productivity, there could be regional differences because the value of a worker's life will depend on income distribution and wage differences in the region where it is located, also exposing a situation of environmental injustice. Therefore, the construction of an adequate methodology to monetize the impacts of pollution on health, ecosystems and non-living systems is a project that deserves the attention of environmental and health authorities in the Megalopolis region.

The importance of air quality monitoring data and modeling capacities

Regulatory policies generally focus on reducing emissions from various sources; however, it is difficult to anticipate the impact these will have on ambient atmospheric concentrations and their damage. There is no simple and predictable relationship between emissions and concentrations, nor between concentrations and damages. This situation is even more complicated for secondary pollutants where complex chemical transformations take place outside the control of management policies. This leads to a trial-and-error process for the prior assessment of compliance with the reduction targets for pollution levels and their effects. This process is complicated by the increase in the number of sources, the complexity of the emissions, and the extension of the study area.

Air quality monitoring networks are the main source of data for assessing changes in pollutant concentrations associated with emission reductions. However, these networks do not have the spatial resolutions necessary for cost-benefit assessments or often perform poorly and their data can lead to erroneous inferences. The lack of air quality data explains in part the absence of cost benefit assessments of environmental management programs in the Megalopolis. Although the data could be obtained from modeling, satellite platforms or low-cost sensors, their use could increase the uncertainty of the evaluations.

Monitoring in combination with numerical models can provide information on regional impacts of pollution from other urban regions, forest fires, or transboundary transport. Air pollution modeling can fill the spatial gaps of air quality monitoring networks and provides data for the evaluation of impacts on agriculture and non-living systems. Retrospective and prospective studies can also benefit from the use of models. Uncertainties in modeling results can be an important issue when used for impact assessment, however they can be reduced by comparing with observational data, where available, or by using multi-model ensembles with a bias adjustment approach (Solazzo et al., 2018).

6.5. Communication, education, and capacity building

The success and sustainability of environmental policies requires a high level of citizen awareness and active and informed participation of stakeholder (for example, Muñoz-Pizza et al., 2022; Molina, 2021). Mexico City government has maintained an extensive communication infrastructure and deploys various strategies to disseminate information to the public. SEDEMA has a website that, in addition to disseminating the air quality index, offers content on various topics related to pollution and air quality (http://www.aire.cdmx.gob .mx/), includes infographics, annual reports, open data and a specialized space for children (http://www.aire.cdmx.gob.mx/teporingo/). Within the institution is the Directorate of Environmental Culture (*Dirección de Cultura Ambiental*), which is in charge of communication, dissemination, and environmental education activities in Mexico City. In addition, they make use of mobile platforms and social networks for the dissemination of information.

In the rest of the entities of the Megalopolis, there are no communication and education programs, nor an organic structure with specialized personnel and infrastructure for communication and the promotion of environmental education and culture. On the other hand, recently, CAMe launched the campaign "*Pon buen ambiente*" available on social networks, the objective is to motivate the population to carry out actions for the benefit of the environment (https://www.portalambiental.com.mx/calidad-del-aire/20201228/pon-buen-ambiente-para-mejorar-la-calidad-del-aire-y-la-salud).

Regarding capacity development, as mentioned above, there is a disparity between Mexico City air quality management and the other entities of the Megalopolis, this is reflected in the availability of air quality monitoring, the development of robust emissions inventories and the experience in the use of air quality models and forecasts. Although the entities in the Megalopolis have presented ideas for controlling air pollution in their respective ProAire, their progress has been impeded by limited technical capacity to define and implement them. They do not have sufficient information to establish emission standards, emission inventories, and monitoring networks. Monitoring and modeling capacities are weak and there is a lack of research on health impacts.

It is essential to improve the capacity of the human resources for the analysis, formulation, execution and evaluation of the policies and programs aimed at improving the quality, including collaboration with national and international institutions. For example, in January 2020, LTMCE2 organized a symposium and an intensive training workshop on the modeling of air pollution and the evaluation of air quality control strategies, with the collaboration of the University of California in San Diego at the UNAM computer lab. About 35 applicants from academic, research, and government institutions participated under the guidance of Mexican and international air quality modeling experts. Subsequently, an online tutorial was developed and implemented, which is now part of the air quality modeling course at UNAM and is available to others interested in learning about the topic.

6.5.1. Risk communication

The Risk Index for Susceptible People (IRPS) of Mexico City

Considering that the population is exposed to not one but multiple pollutants, that there is no evidence of a safe threshold of exposure to pollution, and that some people are more sensitive to pollution than others and can have effects even at low concentrations; in 2017 SEDEMA and the Marron Institute of New York University developed the Risk Index for Susceptible People (IRPS) (http://www.aire.cdmx.gob.mx/conoce-tu-numero-iner/, accessed March 31, 2023; Cromar et al., 2021). The IRPS is a health-based index that captures the additive effects of multiple pollutants on public health risk with the aim of improving risk communication. It is complementary to the Air and Health Index described by NOM-172-SEMARNAT-2019, which does not directly use health effects to estimate the daily risk to the population.

In the construction of the IRPS index, a generalized linear model was used to evaluate the association between air pollution (O_3, $PM_{2.5}$, NO_2 and SO_2) and respiratory morbidity (Cromar et al., 2021; CDMX, 2023). A Poisson distribution was used for the model and the day of the week, the length of the study period, the number of days from exposure to response, temperature and relative humidity were included as adjustment variables. The index has the following characteristics:

- It is predictive of respiratory morbidity in two groups: children and adults.
- Includes at least three ambient air pollutants, since indices based on only one pollutant may not accurately capture the overall health risk for a population exposed to multiple pollutants daily.
- The index presents a normal distribution to allow effective risk communication, particularly at relatively low levels of contamination.
- The index is simple and easy to interpret; it provides a single value per day for all of Mexico City directly associated with the health risk from exposure to O_3, $PM_{2.5}$ and NO_2, which is representative of the complex air mixture in Mexico City. It can be reported at a higher spatial resolution (for example, at the monitoring station level or similar to that used by the air quality forecast model).
- It is built considering the observable health risks in the population and uses coefficients developed specifically for the population of Mexico City.
- Uses the air quality forecast to anticipate risk levels.

Due to its design, this index is applied only in Mexico City, it is updated and published daily on the website http://www.aire.cdmx.gob.mx/conoce-tu-numero-iner/.

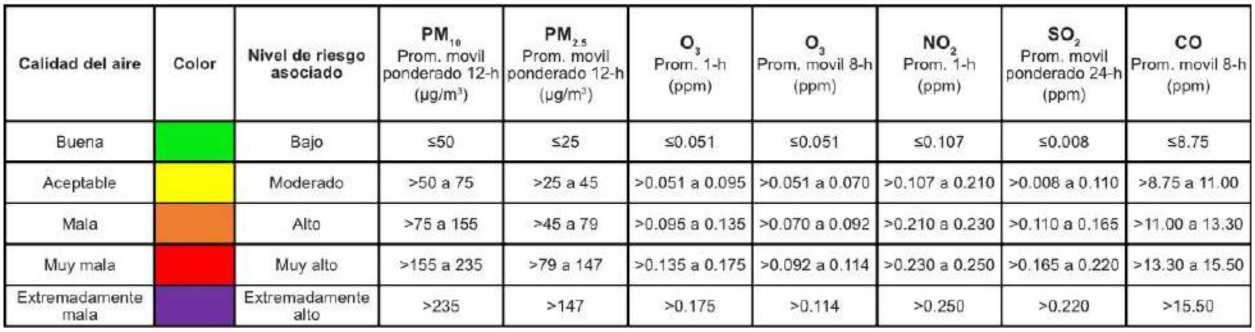
The Air and Health Index

The Air and Health Index is an indicator developed by the Mexican authorities to communicate the degree of air pollution and the probability of an adverse effect on the health of people exposed to pollutants. NOM-172-SEMARNAT-2019 describes the guidelines for its preparation and dissemination.

It is calculated for six air pollutants: PM10, PM2.5, O3, NO2, SO2 and CO, normalizing the concentrations by weighting. It is made up of five bands or concentration intervals that define air quality as good, acceptable, bad, very bad, and extremely bad (see Table 6.3). Each one is associated with a level or category of health risk defined as low, moderate, high, very high, and extremely high (see Table 6.4). Each of these bands, in turn, has a color associated with it: green, yellow, orange, red, and purple, respectively. Unlike the IRPS, the Air and Health Index considers the limit values described in the NOM for each of the pollutants but does not consider the information on morbidity or mortality in its construction.

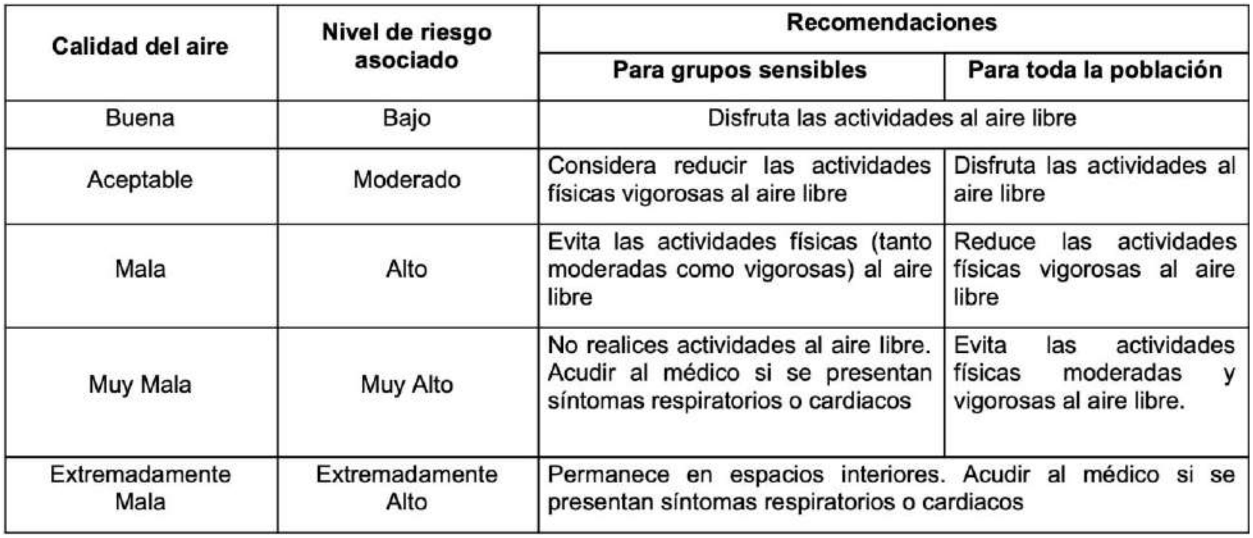
The Air and Health Index is mandatory throughout the country. It should be noted that this index assigns air quality categories and recommendations related to health risk, unlike the previous index (IMECA), which transformed them into a dimensionless scale or index points; however, in the case of the MCMA, the activation of the Atmospheric Environmental Contingency uses the concentration values of the pollutants and not the index.

Table 6.3. Air quality categories and concentration intervals by pollutant of NOM-172-SEMARNAT-2019.



Calidad del aire	Color	Nivel de riesgo asociado	PM_{10} Prom. movil ponderado 12-h ($\mu g/m^3$)	$PM_{2.5}$ Prom. movil ponderado 12-h ($\mu g/m^3$)	O_3 Prom. 1-h (ppm)	O_3 Prom. movil 8-h (ppm)	NO_2 Prom. 1-h (ppm)	SO_2 Prom. movil ponderado 24-h (ppm)	CO Prom. movil 8-h (ppm)
Buena	🟩	Bajo	≤50	≤25	≤0.051	≤0.051	≤0.107	≤0.008	≤8.75
Aceptable	🟨	Moderado	>50 a 75	>25 a 45	>0.051 a 0.095	>0.051 a 0.070	>0.107 a 0.210	>0.008 a 0.110	>8.75 a 11.00
Mala	🟧	Alto	>75 a 155	>45 a 79	>0.095 a 0.135	>0.070 a 0.092	>0.210 a 0.230	>0.110 a 0.165	>11.00 a 13.30
Muy mala	🟥	Muy alto	>155 a 235	>79 a 147	>0.135 a 0.175	>0.092 a 0.114	>0.230 a 0.250	>0.165 a 0.220	>13.30 a 15.50
Extremadamente mala	🟪	Extremadamente alto	>235	>147	>0.175	>0.114	>0.250	>0.220	>15.50

Table 6.4. Messages associated with the categories of air quality and health risks described in NOM-172-SEMARNAT-2019.



Calidad del aire	Nivel de riesgo asociado	Recomendaciones	
		Para grupos sensibles	Para toda la población
Buena	Bajo	Disfruta las actividades al aire libre	
Aceptable	Moderado	Considera reducir las actividades físicas vigorosas al aire libre	Disfruta las actividades al aire libre
Mala	Alto	Evita las actividades físicas (tanto moderadas como vigorosas) al aire libre	Reduce las actividades físicas vigorosas al aire libre
Muy Mala	Muy Alto	No realices actividades al aire libre. Acudir al médico si se presentan síntomas respiratorios o cardiacos	Evita las actividades físicas moderadas y vigorosas al aire libre.
Extremadamente Mala	Extremadamente Alto	Permanece en espacios interiores. Acudir al médico si se presentan síntomas respiratorios o cardiacos	

Limitations

The IRPS is the first exercise in the country to incorporate the evidence of the risk to health of a multi-pollutant environment in an index; this effort can result in an extraordinary tool for the protection of health. Some areas of opportunity to improve the IRPS are described below:

- The index uses risk obtained from studies exploring the impact on the general population, it may not be appropriate to target susceptible populations as this conveys a message that may not be universal, which would discourage its use by people who are not perceived as "susceptible."
- The index requires validation as well as the risk values used in its construction.
- It would be advisable to extend the coverage to the entire MCMA, as well as explore the possibility of increasing the spatial resolution, for example, at the level of zones, municipalities, etc.

The Air and Health Index has managed to harmonize the way in which air quality is communicated in the country, however, some aspects that merit review for future updates include:

- Despite considering various pollutants in its construction, it is not a multi-pollutant index. Could it be improved to reflect the effects of exposure to the complex urban mix?
- It is not a health-based index, therefore including the term in the index name would not be appropriate.
- It is recommended to include a clear description of the bases of the health recommendations and the definition of the different categories.

6.6. Challenges and recommendations

Much progress has been made in combating air pollution problems in Mexico City and in some of the entities in the Megalopolis. Nevertheless, substantial challenges remain to effectively reduce concentrations of harmful pollutants to protect the public health and the environment. Population growth, the expansion of urban sprawl, and the high motorization of the metropolitan area and the surrounding Megalopolis region will continue to generate polluting emissions. In addition, changes in urban landscape and climate change have contributed to progressive increase in the temperature in the MCMA and some other entities in the Megalopolis, potentially affecting local meteorology and air quality. Regional forest fires caused by periods of increasingly frequent and intense droughts induce severe episodes of particle pollution. Except for the MCMA, air quality monitoring, emission inventories and air pollution studies in the Megalopolis are limited, making it difficult to evaluate the regional air quality and the impacts of pollutants in the region in order to design cost-effective emission reduction strategies.

Knowledge gaps

- How to promote the development of scientific knowledge and the creation of research centers outside of Mexico City?
- How does the federal government promote scientific work and capacity development in the entities of the Megalopolis?
- What additional data are needed to design and evaluate the measures of the ProAires of the Megalopolis entities?
- What are the main research needs in the urban centers of the Megalopolis?
- Available evidence suggests that the chemistry and physics of Mexico City’s atmosphere are changing. How can the government lead a new integrated measurement campaign for the Megalopolis?
- What are the scientific lessons learned for environmental management from the restrictions during the COVID-19 pandemic?

Role of CAMe in coordinating regional air quality management

The Megalopolis Environmental Commission (CAMe) was created in 2013 as a coordination body for the planning and execution of policies, programs, projects and actions related to environmental protection, preservation and restoration of ecological balance, in the region that makes up the Megalopolis of central Mexico.

The CAMe is made up of seven federative entities: Mexico City and the states of Hidalgo, Mexico, Morelos, Querétaro, Puebla and Tlaxcala, and also by four federal government ministries: the Ministry of the Environment and Natural Resources (SEMARNAT), the Agrarian, Territorial and Urban Development (SEDATU), Infrastructure, Communications and Transportation (SICT) and Health. It has a Governing Body, which is made up of the Heads of the federal Secretariats, the Governors of the states and the Head of Government. It also has a Scientific Advisory Committee, made up of 15 scientists, academics and experts in environmental matters, who have the power to advise and offer their opinions and recommendations on the Commission's priority actions.

For its operation and functioning, the CAMe has an Executive Coordination, which convenes the sessions of the Governing Body, proposes actions and follows up on the agreements. The Executive Coordinator articulates the actions of eight Working Groups, made up of the technical staff of the entities and institutions participating in the CAMe.

The CAMe has the Trust 1490 to support the Environmental Programs, Projects and Actions of the Megalopolis (FIDAM 1490). It receives annual contribution of $5.00 pesos for each vehicle verification carried out in the verification centers of the entities of the entities of CAMe. FIDAM 1490 can also receive contributions from other sources such as donations, remnants of budget savings from its members, among others.

The CAMe could be strengthened with actions such as the following:

- Include the Ministry of Energy (*Secretaría de Energía*, SENER) and the Ministry of Finance and Public Credit (*Secretaría de Hacienda y Crédito Público*, HACIENDA) of the federal government as members of the Commission, to reinforce the implementation of high-impact regional environmental policies, programs and actions.
- Create an Advisory Council made up of representatives of environmental civil society organizations, and chambers and business associations and services from the environmental sector, where they can give their opinion and follow up on issues of common interest, as well as promote constructive dialogue between environmental authorities and civil society in general.
- Encourage contributions and donations to FIDAM 1490 from other sources, such as the mandatory vehicular verification of emissions from federal license plate vehicles carried out by the SICT, contributions from the industries with the highest polluting emissions, and strengthening the commitment of the contributions derived from the state vehicle verification
- Advance in other priority environmental issues in which the CAMe can contribute to harmonizing programs and actions, for example in the simultaneous and harmonized attention to air quality and climate change, circular economy, water quality issues, waste

and mobility. and transportation, as well as conservation of Protected Natural Areas, among others.

- Initially, make it a priority to support the promotion of the measures established in the ProAires of the entities to reduce emissions of pollutants in the region's atmospheric basins.
- Impel evidence-based evaluation of the effectiveness of programs and projects in budget decisions and public policies, including the creation of performance requirements in grants and contracts to ensure that programs are executed and meet their objectives effectively.

Air Quality Monitoring

Although the ZMVM has a well-developed air quality monitoring network that covers a large part of the urban area, the spatial coverage of air quality monitoring in the growing metropolitan area of Mexico City and the rest of the Megalopolis is limited. In addition, the disparity in data quality makes it difficult to assess air quality on a regional scale.

CAMe has the opportunity to contribute with its management leadership to improve air quality monitoring conditions in the Megalopolis. Section 2.7 of Chapter 2 lists a series of valuable recommendations that must be managed by CAMe and environmental authorities to improve the quantity, coverage, and quality of data from monitoring networks, highlighting:

- Develop strategic Regional Monitoring Network capabilities, including different types of sites (urban, peri-urban, boundary)
- Provide financial support to improve the infrastructure and technical capabilities of the air quality monitoring network in the megalopolis, including training in the analysis and validation of satellite data.

Emissions Inventories

Emissions inventories are an essential air quality management tool for evaluating the progress of emission-control strategies and planning future actions. A detailed description of the challenges and recommendations for improving the emission inventories is presented in Chapter 3.

The MCMA emissions inventory is well developed and is used to inform emission reduction strategies. Section 3.4 of Chapter 3 described the challenges and opportunities that exist to improve emissions inventories in the Megalopolis and that can be truly useful in air quality management. CAMe can contribute decisively to the implementation of the recommendations listed in section 3.4 by serving as a leader in the air quality management process in the Megalopolis. In the rest of the entities there are areas of opportunity for improvement, which include:

- verify the inventory objectives and their alignment with management needs,
- improve spatial coverage and resolution,
- review emission profiles and chemical speciation,
- increase temporal resolution, and
- publish information on calculations and uncertainties.

In all cases it is necessary to include or improve the information on the area sources related to the use of solvents in the residential, commercial, and services sectors. Specific studies will be required to obtain or improve emission factors and activity data, as well as temporal distributions and chemical speciation.

Air quality modeling and forecasting

Numerical modeling is an essential tool to help decision makers in designing air quality policies and in evaluating control measures under present and future emission and climatic scenarios, as well as air quality forecasting. Currently, Mexico City government has implemented an air quality forecasting system to alert the public of high pollution of O_3 and PM event 24 in advance.[3] The model is used in evaluating emission reduction policies for air quality improvement and other co-benefits. However, substantial challenges remain in implementing air quality forecasting system in the rest of the Megalopolis due to the limited availability of air quality monitoring and emissions inventory data needed to support the modeling and forecasting efforts, as well as limited qualified technical personnel involving in air quality modeling and forecasting (see Chapter 4, Section 4.6).

There are forecasting efforts carried out by academic institution. The ICAyCC-UNAM has a 72-hour forecast system for CO, NO_X, O_3, PM_{10} and SO_2 for central Mexico, covering the cities of Toluca, Cuernavaca, Tlaxcala, Puebla and Mexico City; graphic outputs are available online. There are other modeling and forecasting efforts in academia and other entities, but the information is not public.

CAMe could provide the financial resources and be a catalyst to develop a system for modeling and forecasting air quality in the entities of the Megalopolis, including collaboration with national and international experts to provide adequate training.

Transportation and mobility: Integrated transportation-land use-air quality management

The uncontrolled urban expansion and the increased motorization in the Megalopolis are main causes of air pollution and traffic congestion. The creation of a Creating a transport system properly balanced with the environment requires a transversal strategy that integrates the transport sector, changes in-land use, air quality management, and that involves the different agencies (environment, transportation, urban development, energy, and public works) and with public participation. The goal would be less reliance on individual vehicles through the provision of better public transport and measures that allow for more journeys to be taken on foot or by bicycle. Some of the actions in which the CAMe should take the lead for its implementation include::

- Develop public policies for the optimal location of infrastructure and equipment (Compact Cities with mixed land uses).
- Development of inter- and intra-urban mass transport systems (cargo and passengers).

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[3] The forecast is executed at 24 and 48 hours, but the longer the period to forecast, the greater the uncertainty will be, which is why the Air Quality Monitoring Directorate only publishes the 24-hour value on its website and maintains the 48 hours for monitoring and evaluation purposes.

- Orient the urban development of the Megalopolis towards the containment of its expansion (densification of the territory).
- More frequent origin-destination studies for infrastructure planning and improving operations.
- Promote sustainable mobility (telework, high-capacity public transport, walking and cycling)
- Establish incentives for the introduction of low emission vehicles such as electric and hybrid cars, as well as electric motorcycles.
- Consider limiting private vehicle use in heavily trafficked areas.

Atmospheric science

The study of atmospheric processes is fundamental in understanding the impacts and evaluating the best options for mitigating air pollution. Scientific research has played an important role in helping the environmental authorities of the MCMA to characterize emission sources of pollutant species and their transport and transformation in the atmosphere, identify effective emission reduction strategies, and monitor the progress of regulations that are already in place to ensure that programs are successfully implemented. Chapter 4 has provided an extensive list of challenges and recommendations for improving the scientific understanding of air quality in the Megalopolis.

Current observations in the MCMA and other entities in the megalopolis indicate that atmospheric concentrations of pollutants such as O_3 and PM have not decreased to acceptable limits and have begun to increase in recent years, suggesting the need to update our state of scientific knowledge of the processes that control the formation, transport, and fate of these pollutants. A solid understanding on the changes of the meteorology, emissions and processes that control ozone formation and other secondary pollutants in the MCMA and especially in the Megalopolis region, is vital in the design of new policy actions. Some of the research needs that the CAMe must manage for the development of air quality management strategies are described below.

- ***Extensive atmospheric measurements and modeling studies*** are needed to define optimal emission control strategies for the particular entity in the megalopolis, considering the local instituional, technical, economic, social, and political circumstances.
    - The application and validation of air quality models requires spatially and temporarily resolved emissions data as well as knowledge of the meteorology and solar radiation. In addition to commonly measured O_3, NO, NO_2, CO, and PM mass, individual VOCs and PM chemical compositions are needed. This detailed information will require special studies to better understand the causes of such emissions and to measure progress in limiting them.
    - Policy makers should use this information to balance the economic and social benefits of health improvements against the costs of emission control.

- ***Climate Change Impacts on Air Quality and Health***. Climate change can impact air quality and, conversely, air quality can impact climate change. Emissions of greenhouse gases (for example, CO_2, N_2O) and short-lived climate forcers (CH_4, BC, O_3) into the air can result in changes to the climate.

  - Improve knowledge of the impacts of climate change on human health and the environment in the megalopolis region, enhancing the ability of the state and local air quality managers to consider climate change in their decisions to protect air quality and to reduce the impacts of a changing climate, as well as the communities to address climate change effectively and sustainably.
  - Integrate climate change mitigation and emission inventories with air quality management.
  - Quantify the health and economic benefits of reducing emissions of air pollutants and greenhouse gases.
  - Provide tools and resources to develop a more sustainable energy system.
  - Evaluate how different multipollutant/multisector control strategies can affect greenhouse gases and other air pollutant emissions.

Impacts of air pollution

Air pollution adversely affects human health, causes regional haze and acid deposition, damages crops and the ecosystems. However, most studies in Mexico have focused on understanding the impacts of air pollutants on human health. There are information gaps about the impacts on crops, forests, ecosystems, cultural heritage, and public and private infrastructure.

Policies and programs for air quality management in the Megalopolis have already incorporated some of the results of health studies on particulate matter and O_3. However, key questions and issues remain about the relationship between chronic and acute health effects that are aggravated by exposure to poor air quality and the quantification of the health costs and benefits of controlling key emission sources. In this context, it is necessary to:

- Increase resources for research on air pollution and health.
- Generate standards and regulations for other environmental toxics of interest to the region, for example, benzene, polyaromatic hydrocarbons, among others.
- Conduct more studies on composition of particles to estimate their health risks.
- Strengthen and improve air pollution and health surveillance systems.
- Strengthen studies on the impacts and benefits of air quality management programs on health.
- Generate scientific knowledge about the impacts of air pollution on ecosystem, forests, vegetation, and crops..
- Generate evidence on the effects of acid rain on crops, bodies of water, cultural heritage, and public and private infrastructure.

Communication, capacity development and stakeholder engagement

The success and sustainability of environmental policies depend on high levels of citizen awareness and the informed participation of interested parties. Permanent changes in the attitudes and behavior of the population require the development of an environmental culture and improvements in education. Many policies will not work unless stakeholders take ownership of them and share responsibility for their implementation. Their participation can provide support for unpopular but cost-effective measures taken in the public interest, especially if these measures are transparent to the population. It is essential to improve the capacity of human resources necessary to diagnose environmental problems, as well as to formulate, execute and evaluate policies and programs aimed at improving air quality. More trained personnel will improve the performance of the government, the private and academic sectors, and non-governmental organizations. CAMe must be a leader in air quality management by promoting the implementation of the following recommendations:

- Support the ongoing educational activities of the Megalopolis entities aimed at raising environmental awareness among the general public.
- Allocate financial resources for environmental education programs.
- Support air pollution research in universities and government institutions, to strengthen environmental management capacity in federal, state and local government agencies, as well as in the industrial and academic sectors.
- Develop evidence-based information and resources to improve communication with the public and communities, so that they can be better prepared for potential climate threats created by wildfires, floods, droughts and other extreme events, particularly among the most disadvantaged populations. vulnerable.
- Involve stakeholders and the general public in the design and implementation of emissions reduction strategies, including the development of information campaigns on the benefits of reducing emissions for the population.
- Involve communities and non-governmental groups in monitoring and detection studies of high pollution areas through the use of low-cost sensors.

CHAPTER 7. CHALLENGES, LESSONS LEARNED, AND RECOMMENDATIONS

The following summarizes some of the main challenges, lessons learned, knowledge gaps, and research needs regarding the current state of air quality monitoring, construction of emission inventories, development of air quality forecasting models, research in atmospheric science and public health in the Mexico City Metropolitan Area (MCMA) and the other region of the Megalopolis, as well as some policy options to improve air quality and protect the population from the adverse effects of pollution. Detailed descriptions for each of these topics are available in the corresponding chapter under each section heading below.

7.1. Air quality monitoring in the Megalopolis

Challenges of air quality monitoring in Mexico City

Mexico City Monitoring System (SIMAT) has maintained a constant quality in its work over the last two decades, which makes it possible to build trends of the main pollutants and objectively assessing the evolution of the impacts of urban development and the results of management. Despite the growing importance of SIMAT for environmental management and the contribution to the protection and improvement of the health of the large population of the MCMA, the human resources and annual budget allocated for monitoring are limited and could affect compliance with the basic needs of operation and maintenance. Therefore, it is necessary to explore cooperation mechanisms to increase technical and economic participation among the entities that coexist in the MCMA. Due to urban expansion, SIMAT's spatial coverage is limited, mainly in the metropolitan area of the State of Mexico.

Challenges of air quality monitoring in the Megalopolis

Air quality monitoring in the region has focused mainly on main urban centers. therefore, there is little information on the spatial representativeness of the networks/stations based on the monitoring objectives and information on the air quality situation in the peripheral urban settlements, rural areas, and natural areas. Despite the fact that in most of the entities that make up the Megalopolis, air quality monitoring has been carried out for more than a decade, the monitoring systems present different levels of maturity, which is directly reflected in their operation and performance with a significant disparity in data quality. Most networks do not have monitoring objectives, data quality objectives, or adequate plans or protocols for quality control and assurance. Metrics for quality assessment during data monitoring and validation are unknown. There is little information on the level of certainty of the data and the impact of this limitation on the decision-making and on the fulfillment of management goals.

Although this document does not intend to carry out an evaluation of the performance of the monitoring networks, from the review of the public data some key aspects emerged that require the attention of the environmental authorities and which are mentioned below:

- The region of the Megalopolis is underrepresented by atmospheric monitoring. There are important gaps in the spatial distribution of pollutants both at the urban and regional scales. There is little evidence on the air quality situation in areas of ecological value, agricultural extensions (important for food security), and small towns.
- There are challenges in reducing the disparity in data quality between different monitoring systems, in some cases the data have uncertainties that are difficult to quantify, limiting their use for air quality management and for public information.
- Some air quality monitoring systems do not carry out adequate validation before publishing their data in their local repositories or in the National Air Quality Information System (*Sistema Nacional de Información de Calidad del Aire*, SINAICA). Deficient data must be identified and invalidated during the monitoring process before publication. On the other hand, the approval and publication of these data in the SINAICA repository gives a false sense of confidence to these monitoring networks that are producing deficient data.
- The lack of economic, technical, or human resources is a constant in all monitoring systems. This is a very important limitation that must be addressed, since air quality management depends on them and they are also tools for public health protection.
- Most monitoring systems do not have an adequate data quality management program.
- All monitoring systems report pollutant concentrations that exceed the limit values of the Official Mexican Standards (NOMs), mainly for ozone (O_3), particles smaller than 10 µm (PM_{10}) and particles smaller than 2.5 µm ($PM_{2.5}$). The highest O_3 concentrations are observed during March to May, while those of suspended particles (PM) are observed during the dry season. During the rainy season (June to October) pollution levels decrease throughout the region. It is important to note that two of the most polluted days are usually observed in Christmas and New Year's Day due to the burning of pyrotechnics.
- Acid rain continues to be a problem in the territory of Mexico City; however, environmental management has been unaware of this problem and the situation in the other entities of the Megalopolis is unknown.

Recommendations to improve air quality monitoring in the Megalopolis

The recommendations presented below are intended to invite local and federal authorities to carry out a diagnosis of how the monitoring networks are operating and the quality of the data they are collecting. This will allow them to take the necessary actions to improve the performance of atmospheric monitoring in the Megalopolis region. The list of recommendations presented here is not exhaustive, but it does cover the major deficiencies found in air quality monitoring networks during the preparation of this document.

- ***Implement system audits and technical evaluations***. Conduct system audits and technical evaluations of the monitoring networks in order to identify their capabilities and deficiencies at each stage of the process. These evaluations must be carried out with specialized personnel, preferably by independent third parties unrelated to the monitoring programs. Based on the results, establish realistic goals and work plans to guarantee the continuous and permanent improvement of the proper operation in the short term.

- ***Implement quality control plans.*** Design and establish standardized plans for quality assurance and control in the different stages of monitoring, with the purpose in advancing the harmonization of the quality of the data generated throughout the region. Establish appropriate quality metrics to assess the quality of the work carried out by the monitoring networks..
- ***Define objectives and validation metrics***. Define objectives, criteria and metrics for data validation, prior to submission to SINAICA, as well as validation protocols prior to publication.
- ***Evaluate spatial representativeness***. Develop protocols for the evaluation of spatial representativeness and, based on them, carry out a review of the location and of the pollutants measured at all the monitoring stations in the region. In those where their location compromises the monitoring objectives, carry out the necessary actions for their relocation, using harmonized protocols based on scientific evidence (for example, regional air quality models).
- ***Incorporate long-term financing mechanisms.*** Guarantee the sustainability of monitoring networks with appropriate budgets that include state (and/or municipal) and federal participations. Explore financing mechanisms, for example, trust funds, as well as the participation of private resources, such as foundations that allow the operation of monitoring networks in the long term.
- ***Establish monitoring in non-urban areas.*** Consider the establishment of monitoring stations to cover spatial gaps, generate data on pollution levels in rural areas and in areas of ecological interest. Incorporate environmental justice criteria in the selection of monitoring sites.
- ***Retrospective validation of data.*** Based on the monitoring objectives, carry out a retrospective analysis of the data generated by the different monitoring systems and identify with appropriate flags those data of questionable quality.
- ***Strengthen monitoring infrastructure***. Through the Program to Strengthen Air Quality Monitoring Capacities in the Megalopolis, 150 million pesos were allocated to strengthen the monitoring infrastructure and support a Megalopolitan Air Quality Monitoring System. As of December 2022, the program showed a physical and financial progress of 94%. Although there is evidence of the equipment and infrastructure acquired, the presentation of clear and objective evidence of the benefits achieved in the improvement of monitoring, in the quality of the data and in the dissemination of information by the funded entities is still pending.
- ***Expand technical capabilities.*** Develop continuous training programs to increase the technical capabilities of the personnel of the atmospheric monitoring networks.
- ***Incorporate satellite measurements.*** The increasing availability of satellite data and a new generation of satellite air quality monitoring may provide scientists and policy makers with additional information on concentrations of criteria pollutants, which may be valuable for regions of the Megalopolis outside the coverage of monitoring networks. However, satellite data will not replace surface monitoring, they are complementary. It is necessary to

establish new stations and continue monitoring ambient air quality on a routine basis with regulatory grade instruments in such areas.

- ***Incorporate calibrated and validated low-cost monitors.*** Recent developments in sensor technology have improved the performance of low-cost monitors and allow them to be used in particular conditions to complement current monitoring systems and create new applications to better report the status of air quality. However, this will only be possible if a robust calibration and validation scheme is put in place to reduce uncertainties in the measurements.
- ***Public dissemination of information.*** It is important to maintain the permanent dissemination of the monitoring results to the population through the mass media, websites, applications and social networks.

7.2. Atmospheric pollutant emissions in the Megalopolis

Challenges and recommendations to improve the estimation of emissions

- ***Incorporation of quality control methods during the construction of emissions inventories***. It is important that the working groups, which include the government authorities responsible for the development of emissions inventories that are relevant to the Megalopolis implement the quality control methodologies that are available during the preparation of emissions inventories. The systematic application of quality control during the elaboration of an inventory is crucial to obtain coherence, integrity, comparability, representativeness, and transparency of the information obtained.

  The application of quality controls will make it possible to identify the main areas with uncertainty in the inventory, as well as the existing challenges to improve the estimates in each successive version. Quality control must be incorporated with statistically robust techniques parallel to the preparation of the inventory and not after. One of the main challenges to systematically incorporate quality control processes is to institutionalize support for working groups in terms of allocating the necessary financial, infrastructure, and training resources.

- ***Independent evaluation of inventories.*** The National Inventory of Emissions of Mexico (*Inventario Nacional de Emisiones de México*, INEM), the National Inventory of Emissions of Greenhouse Gases and Compounds (*Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*, INEGYCEI) and the Emissions Inventory of the MCMA (*Inventario de Emisiones de la ZMVM*, IE-ZMVM) generally use a combination of methods for estimating emissions, which include: (1) direct sampling of sources (mainly for industrial sources); (2) indirect estimates using a combination of mass balance techniques and models, for example, MOVES-Mexico, the Mexican Biogas Model, the Non-Road model for off-road sources, and the Emissions and Dispersion Modeling System (EDMS); (3) extrapolation techniques for combining emission factors with activity data, and (4) the Intergovernmental Panel on Climate Change (IPCC) guidelines for estimating greenhouse gas (GHG) emissions.

The joint application of the various methods represents a significant effort to obtain, process, and analyze the information necessary to develop the emission inventories. However, it is necessary to incorporate techniques to assess uncertainty and independent reviews. Estimated emissions inventories must be based on the verification and analysis regardless of the sources of information used. The first challenge to be solved is the systematic promotion of the work and the continuous collaboration with federal, state and local institutions and agencies that generate and process the activity data information to ensure consistency between reported data, the approximations used, and the data obtained under real operating conditions.

The experience of the field measurement campaigns in the MCMA in 2002, 2003, and 2006 showed that joint information from field studies, modeling activities, monitoring networks, focused consultations and guided visits, is an important tool that can be used successfully for evaluation and analysis of emissions estimated in local inventories. Valuable tools for independent assessment of emissions use indirect methods such as independent emissions modeling in combination with emission measurement campaigns, as well as long-term studies with the joint application of various techniques, including remote sensing for mobile and industrial sources, inverse modeling techniques, satellite information processing, eddy covariance flux towers for area sources, sampling in tunnels and with portable systems for vehicular emissions.

- ***Updating of emission factors and activity data.*** Due to the continuous changes in technology, fuel regulatory requirements, and changes in the activities that affect the emission processes, it is necessary to periodically update both emission factors and activity data. It is essential that the environmental authorities of the Megalopolis promote field studies and surveys to update the information used in inventories.

  There are key emission sources that must be prioritized for periodic updating of emission factors and activity data, examples of these sources include: gasoline vehicles, all-terrain vehicles, motorcycles, heavy-duty diesel vehicles, and those used in the transportation of passengers and cargo. Emissions from the resuspension of dust on roads, volatile organic compounds (VOCs) from paints, the handling of solvents, disinfectants, cleaners, waterproofing and infectious waste, as well as cooking in the informal sector and from services are examples of key sources with high uncertainty in their estimates and which must be continuously reviewed.

- ***Coordination between environmental authorities and working groups that develop emission inventories.*** It has been observed that each entity that makes up the Megalopolis is both an emitter and a receiver of pollutants, so it is necessary to strengthen coordination between the different entities to improve emission estimates at the regional level. In addition, it is essential to improve coordination between the working groups that prepare emissions inventories, which will allow the generation, processing and analysis of information to be efficient and transparent. This will contribute to improving air quality management and reducing pollution levels in the Megalopolis. It is important to understand the regional emission and transport of pollutants to coordinate control measures within the

Megalopolis. Many public policies will only be able to maximize their benefit if there is coordination between the government agencies of the different entities.

- ***Increase and expand technical capabilities***. As part of the implementation of a process to improve coordination between environmental authorities, it is also important to increase and expand the technical capacities for the preparation of inventories by the working groups of the different entities of the Megalopolis at the federal, state, and municipal levels. Better coordination and technical capacity are necessary steps to generate (in successive versions) a regional emissions inventory for the Megalopolis that is comprehensive, robust, precise, reliable, and that serves as support for modeling, forecasting, and the design of programs that allow to improve air quality. It is necessary that the reports of the emissions inventories, the calculation methodology and the management of uncertainties be publicly accessible.

- ***Improve the estimation of mobile sources*.** In the case of vehicle emissions, most inventories in Mexico are currently being developed using the MOVES-Mexico model, which is an adaptation of the MOVES (Motor Vehicle Emissions Simulator) model of the United States Environmental Protection Agency (US EPA). The MOVES-Mexico model allows emissions to be estimated by adjusting the calculations with local databases such as data from monitoring campaigns with remote sensors, data from vehicle verification programs, emissions tests on new vehicles and fuel formulation, in addition to the weather conditions and local and regional characteristics. However, a major challenge in fitting mobile source emissions using the MOVES-Mexico model is the adequate representation of real driving conditions. Therefore, due to the particularities of traffic that different cities have, the estimates of emission factors and activity data must be improved.

  The first version of MOVES-Mexico was used in the country in 2016, making adjustments to the United States MOVES model version 2014a, for estimating emissions from on road vehicles. In 2022, the model for Mexico was updated and known as MOVES-Mexico 2022, adjusting the databases with recent information from remote sensors, vehicle verification programs, fleet, and vehicle activity. The model will be publicly available during the second half of 2023.

  The MOVES-Mexico 2022 version was based on the 2014b version of the United States MOVES, instead of MOVES3, which was published by the EPA in 2022 and included the state of the science on emissions from mobile sources. However, the MOVES3 modifications would not apply in Mexico, since they present new emissions measurements in the United States and also adjustments to the emissions of off-road vehicles whose emission factors have not been evaluated for Mexico.

  As part of the Short-Lived Climate Forcers (SLCF)[1] campaign, coordinated by the MCE2 in Mexico City in 2013, the components of suspended particles (black carbon (BC), organic carbon and other inorganic components of $PM_{2.5}$) and gases (carbon monoxide (CO), nitrogen oxides (NO_X), sulfur dioxide (SO_2), VOCs) present in the emissions of various

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[1] Short-lived climate forcers (SLCFs) are also known as short-lived climate pollutants (SLCPs).

diesel vehicles (buses, cargo trucks) with different model years and emission control technologies were determined, under real driving conditions using the chasing technique with the Aerodyne Mobile Laboratory (see Chapter 4, Section 4.5). Comparison of the results with the US-EPA MOVES model 2014b showed disagreements for several species, demonstrating the need to use a database with locally obtained emission factors to reduce uncertainty in emission estimates. It is necessary to consider not only adjusting the MOVES-Mexico model to local conditions, but also updating its base version to improve estimates.

Also in 2014, emission factors for gases (CO, CO_2 and NO_X) and suspended particles (the BC component and total PM) were also obtained for a variety of off-road diesel vehicles (construction and agricultural equipment) with and without diesel particulate filters, using the technique of Portable Emission Measurement Systems (PEMS) in high temporal resolution. Results showed that reductions for BC emission factors were significantly greater (>99%) with installed filters. Unlike on-road vehicles, there is no regulation for the emission levels of off-road vehicles in use. Their relative contributions increase over time as road vehicle emissions continue to be reduced through the use of better technologies. There is a great need to increase the database of emission factors for off-road vehicles through field studies and to continue studying the benefits of off-road vehicle emission control technologies in the Megalopolis.

In addition to emissions from automobile exhaust systems, it is important to characterize evaporative emissions from the fuel system and those from wear and tear of tires, brakes, and other non-exhaust systems, which include toxic metals.

Currently, the project “Emissions inventory of pollutants from on-road mobile sources for the Megalopolis with base year 2018 and the update of the MOVES Mexico model” (*Inventario de emisiones contaminantes de fuentes móviles carreteras para la Megalópolis con año base 2018 y la actualización del modelo MOVES México)* by CAMe and SEMARNAT, financed with resources from FIDAM-1490, is underway. This project will support and provide training to the seven entities that make up the CAMe for the development and updating of their emissions inventory.

- ***Improve the estimation of evaporative emissions from fossil fuels***. The control of fuel losses due to evaporation during the handling and supply processes must be based on a comprehensive strategy of regulation, optimization, updating and improvement of service stations, as well as the application of technical methods to measure emissions and evaluate their efficiency. It is necessary to guarantee the reduction of emissions during the sale through the use of Vapor Recovery Systems (VRS), whose operation must be continuous and efficient in accordance with NOM-004-ASEA-2017. The NOM-006-ASEA-2017 establishes the specifications, technical criteria and requirements for industrial safety, operational safety and environmental protection that must be carried out in land storage facilities for petroleum and petroleum products. The standard establishes that the facilities must control gasoline vapors during the loading of tanker trucks with an efficiency equal to or greater than 95%, but it does not establish test methods, so there is currently no evidence of its operation and quantification of emission control. Similarly, NOM-005-

ASEA-2016 indicates that service stations must have hermetic devices to control gasoline vapors during the unloading of tanker trucks. However, the standard does not establish the test parameters or methods. Currently, a CAMe project is evaluating the coverage and performance of VRSs at gas stations and will propose modifications to NOM-005-ASEA-2016 and NOM-006-ASEA-2017.

- ***Improve estimates of industrial sources.*** The estimates mainly apply US EPA emission factors, which are not necessarily applicable to the operating and technological conditions of industrial processes in Mexico. Furthermore, when rigorous quality control is not followed, the calculations tend to have errors and the vast majority of the data recorded in the Annual Operation Certificates (*Cédulas de Operación Anual*, COA) do not have the necessary operational representativeness for emissions inventories. The data are recalculated considering activity data, historical information and other information sources, since the industry reports have multiple errors. Several entities do not have the annual reports from the industry under state jurisdiction or they do not report annually or reliably. There is also large uncertainty regarding fugitive emissions and the operating efficiency of control systems reported by the industry. These limitations underscore the need to reduce uncertainty in the estimates from industrial sources.

- ***Improve estimates of area sources.*** Area sources of air pollutants are small but numerous and contribute significantly to PM, CO_2, VOCs, ammonia (NH_3), SO_2, and toxic compounds emitted from diverse sources including: product storage and transport distribution (gasoline, LPG), commercial and domestic use of solvents, consumer products, waste management (landfills, open trash burning, wastewater treatment, sewage), agricultural activities (crop burning, tillage, application of fertilizers and pesticides, cattle feedlots, enteric fermentation, manure management), dust resuspension, among others. In contrast to large stationary sources, area sources are generally required to meet less stringent emissions limits. Many of the micro industries belong to the informal industry sector which are not effectively regulated; they are too small to be inventoried, contributing to one of largest uncertainties in emission estimates. For example, area sources contributed to 66% of VOCs in the MCMA in 2018. There are numerous small manufacturing, painting, mechanical service workshops, among others, which are part of the informal sector that together can have significant contributions of some pollutants such as VOCs. As the emissions of urban VOCs from transport-related sources have decreased due to technological advances and regulatory measures, volatile chemical products from sources such as personal care and household products, aerosol coating, painting, solvent use and pesticides have gained in importance, highlighting the need for regulatory actions to control the sources. As described below under specific categories (VOCs, biomass burning, greenhouse gases), it is important to support field measurements to estimate the emission factors for area sources, as well as studies to improve the estimate of activity data.

- ***Characterization of emissions of VOCs and toxic organic compounds.*** Volatile organic compounds (VOCs) are of interest in part because they participate in atmospheric photochemical reactions that contribute to O_3 formation and they play a role in the formation of secondary organic aerosols. Additionally, many individual VOCs are known to be harmful to human health (air toxics).

The inventory of VOCs emission is one of the largest uncertainties in emissions estimates. VOCs in the MCMA during 2018 are emitted from a variety of sources, including motor vehicles, chemical manufacturing facilities, refineries, factories, consumer and commercial products, and natural (biogenic) sources (mainly isoprene and monoterpenes from trees). Around two thirds of the total emissions (66%) are generated by area sources, including the commercial and domestic use of solvents, along with LPG leaks (mainly propane and butane).

The commercial and domestic use of solvents contributes about 32% of the total VOC emissions. Within this activity, certain products have a greater contribution, such as personal care products, pesticides and other products for domestic consumption, industrial cleaners, architectural coatings and automotive care products. With this in mind, the creation of standards that limit the VOC content in priority products should be encouraged, while at the same time promoting the acquisition of merchandise with lower content of these substances. Efforts to control VOC emissions should also focus on addressing LPG leaks in homes, businesses, services and industries, which together generate 20% of emissions. Measures are required to reduce leaks, promote responsible consumption of this energy, and move towards more environmentally friendly fuels and renewable-energy technologies, such as solar heating system and solar water heaters.

Toxic pollutants are compounds that have the capacity to directly produce adverse effects on the health of the population or the environment. Most of these pollutants are VOCs such as toluene and xylenes, although the classification also includes elements such as lead, other heavy metals, phosphorous, and their compounds.

Toxic organic compounds represent 29% of total VOC emissions and area sources are the main emission source, with a contribution of 69% of total toxics in the MCMA in 2018. The main emitting activities are related to the domestic and commercial use of solvents, urban waste management and gasoline distribution.

Efforts are currently underway to improve the characterization of unregulated toxic organic compounds in the Megalopolis. An example is the use of aerosol thermal desorber techniques - gas chromatograph - mass spectrometer (TAG-GC-MS) by the Atmospheric Sciences group at ICAyCC-UNAM. The objective is to improve the understanding of the origin of compounds such as polycyclic aromatic hydrocarbons (PAH) and their relationship with mobile, industrial sources, solvents, household products, paints, waterproofing, garbage, and personal use products, among others.

Due to its relevance in atmospheric chemistry and its toxic effects, it is important to maintain and increase support for studies aimed at the characterization of VOC emissions and toxic organic compounds. In addition to characterizing the chemical speciation of VOCs, studies should prioritize a better understanding of the spatial and temporal distributions of organic compounds in the Megalopolis.

- ***Emissions from motorcycles***. An important challenge is the regulation of the use and improvement in the estimation of emissions from motorcycles in the Megalopolis. In recent years, the growth in the use of motorcycles in the region has been explosive. Among other factors, the growth is due to the versatility of this type of units to circulate under conditions of high traffic congestion (generally ignoring traffic regulations), the lower acquisition price, and the lack of adequate regulation. The importance of regulating the use and maintenance of motorcycles, as well as improving the estimates of their emissions, lies in the fact that they can potentially circulate with highly polluting emitting technologies and can negatively impact air quality. Currently there are no regulations for motorcycle emissions, but SEMARNAT is coordinating a working group for the preparation of a NOM project to limit its emissions.

- ***Improve estimates from biomass burning and dust storms***. Biomass burning is one of the largest sources of trace gases and aerosols emitted to the global atmosphere and is the dominant source of BC and primary organic aerosols. Smoke from the fire is also a major source of greenhouse gases, including CO_2, methane (CH_4), and nitric oxide (N_2O). Other emitted pollutants include CO, volatile, semi-volatile, and nonvolatile organic compounds, NO_x, NH_3, hydrogen cyanide (HCN) and nitrous acid (HONO). There are many sources and fire types related to biomass burning emissions; some are natural sources such as uncontrolled and unplanned wildfires, while others, such as emissions from burning of crop residue, municipal solid waste, residential wood burning for cooking and heating, and biofuel for brick production, are the results of human activities. Different approaches had been used to estimate emission factors for biomass burning in Mexico City and the surrounding region, including direct measurements over fires in field experiments, aircraft measurements and laboratory measurements as part of the MILAGRO and SLCF campaigns. Despite important advances in the measurement of emission factors, detection and quantification of biomass burning, there is still a need to improve the accuracy in the activity estimates for both open burning and biofuel use.

  The evidence suggests that the exceptional episodes of high level of pollutants in the region are linked to particular meteorological conditions in conjunction with the contribution of large regional emission sources such as the burning of biomass (agricultural and forestry) and the emissions of particulate matter from bare and eroded soil. It is important to promote and support field, monitoring, satellite, and modeling studies to better characterize emissions from these sources and thereby manage the procedures to be followed by the population and environmental authorities during environmental contingencies.

- ***Improve estimates of greenhouse gases***. The IPCC guidelines are generally used to estimate GHG emissions with comparable techniques in all countries, including Mexico. As part of the SLCF campaign, coordinated by MCE2, to characterize the main sources of BC, CH_4 and associated pollutants, field studies carried out in Mexico to study CH_4 emissions from wastewater treatment plants and livestock enteric fermentation indicated that the IPCC methodologies are an inaccurate tool for estimating local greenhouse gases (see Chapter 4, Section 4.5). It is important to determine specific emission factors for each emission source in order to more accurately estimate GHG emission inventories. Based on these best estimates, more effective mitigation policies can be identified and applied.

In addition, field studies demonstrated the importance of obtaining BC emission factors and associated pollutants under real operating conditions from on- and off-road vehicles, brick kilns, stoves, in order to improve emission estimates, since Mexico was the first country committed to reducing the BC as part of its NDC (National Determined Contribution) to the United Nations Framework Convention on Climate Change (UNFCCC).

- ***Incorporation of satellite and remote sensing data for the evaluation of emissions*.** There is an effort on the part of the academic sector in conjunction with environmental authorities to incorporate the use of satellite information as a tool for evaluating emissions inventories. An example is the use of NO_2 and formaldehyde (HCHO) columns from the Sentinel-5P TROPOMI instrument to assess changes in emissions in regions of the Megalopolis. Due to their large potential for evaluating emission estimates in inventories, it is important that the use of these techniques be expanded in Mexico. The incorporation of satellite data for the evaluation of emissions should also include the application of techniques that characterize the vertical structure, mixing, ventilation, and dispersion processes of the atmosphere such as ceilometer measurements, radiosondes, Doppler lidars and modeling exercises. The integration of these techniques is necessary to understand and predict the interaction between emissions, meteorology, and pollution levels in the Megalopolis.

7.3. Atmospheric scientific research in the Megalopolis

Lessons learned, knowledge gaps, and research needs

Below is a summary of some of the main lessons learned, knowledge gaps and research needs regarding the current state of scientific knowledge on the sources and processes of formation and destruction of air pollutants in the MCMA and the other regions of the Megalopolis described previously.

Sources and processing of atmospheric pollutants

Lessons learned

- The MCMA-2003 and MILAGRO studies suggest that, during the first decade of this century, the atmosphere of Mexico City was highly sensitive to VOCs in the urban core but could be VOC- or NO_X-sensitive in the surrounding region depending on meteorological conditions. Recent study indicates that it is likely there is a substantial spatial difference in the sensitivity of O_3 to VOCs, including important differences in various areas of Mexico City and its periphery.
- The levels of primary pollutants (such as CO, NO_2, SO_2) in the MCMA are highly sensitive to changes in anthropogenic emissions. This was demonstrated during the fuel supply problems in January 2019 and in the effects of the suspension of activities and mobility restrictions during the COVID-19 pandemic after March 2020.

- Experience gained from changes in emissions resulting from drastic measures taken by the governments during the COVID-19 pandemic shows that the formation of secondary pollutants such as O_3 was not controlled by changes in primary pollutants in the proportions in which they were reduced. Furthermore, this highlights the importance of meteorology and episodic contributions when analyzing air quality during large emission reductions. During the pandemic, the activity and distribution patterns of the vehicle fleet, as well as domestic and service activity, were modified; this could have had impacts on the concentration and variety of precursors and, consequently, on the chemical reactivity of the atmosphere.
- Non-linear relationships between precursor pollutants and the formation of secondary compounds (including their effects on peak concentrations) should be investigated under various meteorological conditions, along with climate change and socio-economic drivers that may affect future air quality in the Megalopolis,
- The effects of changes in the ratio of precursors and variations in the chemical composition of VOC emission profiles (both those from fossil fuel combustion and evaporative processes) on the formation of secondary pollutants should be investigated under various meteorological conditions in the Megalopolis.
- The production of secondary aerosols responds to changes in the composition of their precursors and meteorological conditions, therefore the sensitivity to the different gaseous compounds forming them under different meteorological contexts should be investigated.

Knowledge gaps

- What meteorological processes control the temporal and spatial distribution of gaseous and particulate pollutants in the atmosphere?
- What are the emerging factors (for example, new emission regulations, changes in technology, social behaviors) that intervened in the formation of pollutants in the Megalopolis and how can they be controlled?
- Has O_3 production changed in the MCMA? In which sectors of the city is O_3 production sensitive to VOCs or NO_X? Are there seasonal, weekly, and diurnal transitions between chemical regimes?
- What are the current profiles and spatial distribution of mixtures of VOCs, semi-volatile organics, persistent organic compounds in the Megalopolis? What are the contributions of these compounds to the formation of O_3 and secondary organic aerosols (SOA)??
- What are the impacts of air pollution on the natural ecosystems of the Megalopolis?

Impacts of Tula-Tepeji on the air quality of MCMA and the megalopolis region

- Why fuel quality has not improved in the Tula-Tepeji corridor?
- Is it possible to establish a monitoring system for emissions from the industrial complex? What are the viable alternatives to reduce emissions from priority sources?
- What is the content of toxic compounds in the plumes that carry air pollutants from Tula?

- How do emissions contribute to the burden of disease associated with air pollution in and around Tula, as well as plume trajectories?
- How do emissions from the industrial corridor affect other cities in the region, for example, Toluca, Pachuca, Tulancingo, San Juan del Río?
- Is there any impact of atmospheric acid deposition on agricultural areas and conservation land in the entities of the Megalopolis?
- In addition to the Tula-Tepeji industrial corridor, are there other sources of anthropogenic pollution with regional impact?
- How do regional contributions of anthropogenic pollutants affect management goals in the entities of the Megalopolis?

Regional scientific research

- The information available from monitoring indicates that some cities within the Megalopolis have pollution levels similar to and even higher than those observed in the MCMA.
- Air quality management programs require strong up-to-date scientific support for the development and evaluation of control strategies to improve regional air quality.
- Scientific studies that allow us to understand the transport and transformation processes of pollutants are scarce outside the MCMA. It is necessary to advance in the study of meteorological phenomena related to the regional transport of pollutants, the identification of natural and anthropogenic sources with regional impact, effects on health and ecosystems, impacts on local management goals and the design of strategies to mitigate regional emissions.
- Information on the effects of pollution on human health outside the MCMA is scarce. It is a priority to know the situation in the other entities of the Megalopolis.
- Air quality monitoring in the region is limited; it is necessary to increase monitoring and dissemination for health protection purposes, including non-urban areas and areas of interest for crop protection and forest resources, modeling or validation of satellite data.
- It is necessary to promote institutional, financial, and technical efforts to reduce the disparity in monitoring, emissions inventory, modeling, scientific research, and management activities in the region under the coordination of CAMe.

Local meteorology and air quality

Lessons learned

- It is necessary to study the characteristics of the planetary (or atmospheric) boundary layer and its effects on air pollution. Meteorological (for example, wind, temperature, humidity) and aerosol profilers have proven to be a robust tool to measure and investigate with high temporal resolution the behavior of various variables in the planetary boundary layer. The study of the properties of the boundary layer requires multiple techniques, combining remote sensing with radiosonde observations, where each of them will provide different information on the mixing, ventilation, and dispersion processes.

- Open questions remain about the different processes in the boundary layer that control mixing and the surface concentrations of pollutants, as well as the interaction of boundary layers between neighboring basins, so different synchronous instruments are needed at multiple locations to better understand their temporal and spatial variability.
- The studies presented in Section 4.4.2 in Chapter 4 describe recent knowledge about the mixed layer, its daily and seasonal variability, and the potential uses of the ceilometer to better understand the relationship between the mixed layer and air quality. However, many questions regarding how this interaction influences extreme pollution events in the context of climate change remain to be investigated.
- The possible effects of radiation on the formation of O_3 is a relevant aspect for management; it has been observed that with the increase in solar radiation, the production of O_3 also increases.
- The ProAire 2021-2030 considers the reduction of aerosols, however, its compliance could induce an increase in O_3 concentrations due to the increase in solar radiation that reaches the surface. On the other hand, the changing climate could impact the formation processes of secondary pollutants.

Knowledge gaps and research needs

- What is the intensity of the urban warming in the different urban conglomerates in the Megalopolis?
- How does the urban warming affect the micrometeorology of the cities in the Megalopolis?
- What impacts does urban warming have on the regional climate and atmospheric chemistry?
- Should management plans consider the effects of urban warming on pollutant reduction goals? Should they include actions for their mitigation?
- What are the expected effects of climate change on meteorology and air quality in urban and non-urban regions in the entities that make up the Megalopolis?
- How do meteorological changes on global, regional and local scales influence episodes of high urban pollution?
- The available evidence indicates with a certain degree of certainty that the increase in temperature will bring changes in the chemistry of the atmosphere and in the production of O_3, however, there is large uncertainty in the magnitude. The concept of climate penalty refers to the possible increase in the concentration of O_3 in environments with high levels of its precursors. In this sense, how will the climate penalty affect the reduction goals of the different management plans? Should management plans include climate penalties?

Short-Lived Climate Forces

Black carbon emissions from on-road and off-road diesel vehicles section

- The results from field studies in the MCMA highlight the need for using locally-obtained emission factors database for developing countries to reduce the uncertainty in the emissions estimates and to improve the evaluation of the effectiveness of emissions reduction measures.
- Estimating emissions from in-use off-road vehicles for construction and agriculture is challenging because the extent of emission factor datasets available is considerably more limited compared to on-road vehicles.
- Due to their durability, off-road vehicles often remain in service for several decades and thus their relative emissions contributions increase over time as emissions from on-road vehicles continue to be reduced by technological improvements. Thus, off-road vehicles are potentially large contributors to BC emissions in many parts of the world, highlighting the importance of designing emissions control strategies and a strong need to increase the emission factors databases for off-road vehicles through field studies.

Methane emissions from wastewater treatment plants

- Sewage system and treatment plants are an important source of CH_4 and nitrous oxide (N_2O).
- Adopt treatment systems with low energy consumption as this represents more than 60% of total CH_4 emissions
- Improve the operation of primary sedimentation (frequent purges)
- An adequate treatment of the sludge must be given, preferably one that considers the production and use of biogas
- The IPCC Tier 1 methodologies (2006 and 2019) represent an inaccurate tool as they underestimate emissions
- It is important to have determine specific emission factors to more accurately estimate GHG emission inventories. Based on this, more effective mitigation policies can be identified and applied.

Methane emissions from livestock enteric fermentation

- It is necessary to continue conducting studies on CH_4 emissions from enteric fermentation of cattle under different production and feeding systems in Mexico, including other ruminant species such as sheep and goats.
- Strengthen studies to determine specific CH_4 emission factors for manure management for Mexico.
- It is necessary to design mitigation strategies for CH_4 emissions by enteric fermentation of cattle applicable on a commercial scale.

- Strengthen studies to determine specific emission factors for N_2O for Mexico. In this regard, progress has been minimal.
- Carry out analysis of the life cycle of GHG originating from the agricultural sector, and specifically from livestock.

Air quality modeling and forecasting

Improve model development and application

- Employ inverse modeling to complement the evaluation of bottom-up inventories, taking into account its potential to improve the spatial and temporal resolution of the inventory, and to estimate the location and intensity of known and emerging emission sources.
- Allocate resources to reduce uncertainties in inventories, improve profiles and estimates based on measurements, and advance knowledge about the participation of VOCs in the production of aerosols and gaseous pollutants of photochemical origin.
- Obtain data on the characteristics of primary aerosols for different representative environments of the Megalopolis. Obtain meteorological and air quality data outside of urban areas.
- Explore the best model parameterizations for the different regions of interest in the Megalopolis, produce or obtain the data with the appropriate resolutions for the input and evaluation of the model.
- Consider modeling needs within research projects and management policies, increase the spatial and temporal resolution of air quality and meteorological measurements. Include modeling needs in the design of monitoring systems.
- Strengthen the modeling capacities of the region through the construction of an ensemble of models that includes the currently available models (SEDEMA, ICAyCC-UNAM, Querétaro, among others), as well as possible future developments.
- Support the efforts of Mexico City to ensure the continuous improvement of its forecast system and guarantee its sustainability.
- Advance towards the assimilation of data from satellite products and from other observation networks and profilers, which can be used for both case studies and forecasting. With adequate computing power, it is possible to move from limited-area models to multi-scale global models and thus study air pollution in the context of climate change.
- Coordinate inter-institutional efforts in the production, management and processing of data to generate useful products for air quality management.
- Apply machine learning algorithms to improve the physical parameterization of the models, in the estimation of emissions, in the analysis of satellite images and model outputs to adjust the results, and with this, obtain better predictions.

Strengthen human resources:

- Train research personnel in the area of data assimilation, use of satellite information, evaluation of models, evaluation of the application of machine learning in the processes carried out by the models as well as in the evaluation and post-processing of the products obtained in the modeling.
- It is necessary to increase the number of technical personnel for the maintenance of the supercomputing infrastructure and the use of the software.

Develop infrastructure

- Centralization of computer infrastructure and virtualization in the provision of services to provide entities or institutions with computing capabilities, or allocate resources for the acquisition of computer facilities to the entities of the Megalopolis.

Covid-19 impact on air quality

Knowledge gaps and research needs

- The experience during the pandemic showed a new scenario that confirmed the complex interaction between emissions, meteorology and atmospheric chemistry in the urban atmosphere of the MCMA.
- Accurate estimates of NO_X and VOC emissions in the MCMA and surrounding regions are needed to understand the changes in the formation of O_3, $PM_{2.5}$ and other secondary pollutants during the COVID-19 lockdown period.
- It is necessary to understand how the chemical composition of VOCs changed during the pandemic.
- There is sufficient evidence that during COVID lockdown, the transportation sector was strongly impacted, substantially reducing congestion, but at the same time, increasing the traffic of vehicles delivering goods to homes. The industrial sector also decreased its activities, some industries more than others. Food preparation activities at home, in informal sales and in the restaurant sector were modified. However, emissions from products for personal use, household products, paints, waterproofing agents, domestic garbage, waste, disinfectants, cleaners, among others, increased. It is necessary to evaluate how the services and commercial sector modified their operations.
- It is necessary to understand how the contribution of domestic emissions (for example, cleaning products, food preparation, burning and leaks of LPG and CNG) and from sources other than automobiles and industry (for example, agricultural and forest fires, biogenic emissions, evaporative emissions from other sources) contribute to air pollution and influence the production of O_3 and secondary aerosols.
- Based on what was observed during the COVID-19 restrictions in the MCMA, the results indicated that the reductions in emissions from vehicles and industries caused the concentrations of primary pollutants to decrease in ambient air, however, no reduction in O_3 concentrations was observed. Why? How might this affect the air quality management goals and actions applied during environmental contingencies?

- Based on the experience during the pandemic, how do changes in the vehicle fleet and domestic activity modify the chemical reactivity of the atmosphere?
- Given the observed reductions in $PM_{2.5}$, it is necessary to understand how the reductions in precursor emissions modified the chemistry of the secondary formation of aerosols.
- Regional transport of air pollutants during lockdown period:
  - How did the emission sources from nearby states contribute to air pollution levels in Mexico City?
  - How did the emissions from Mexico City contribute to pollution levels in nearby states?
- A thorough characterization of the atmospheric reactivity, radical budget, and secondary pollutant formation during the lockdown period through modeling activities is needed to understand the air quality during the lockdown period:
- A comprehensive VOC speciation during the COVID-19 lockdown will allow to evaluate changes in OH-VOC reactivity.
- A thorough characterization of the local and regional meteorology during the lockdown period is needed to evaluate any potential ventilation enhancement (that is, windy conditions) or favorable condition for photochemistry (that is, more intense solar radiation).
  - What were the meteorological conditions that contributed to high $PM_{2.5}$ and ozone production/accumulation during high pollution days?
  - What regional and local wind patterns helped to disperse the pollutants during the lockdown?

7.4. Public health studies and air pollution in the Megalopolis

Lessons Learned

There is a need to better understand the relationship between chronic and acute health effects, which are aggravated by exposure to poor air quality. This section presents a summary of the lessons learned from recent studies of the health impacts of air pollutants in Mexico.

- ***Incorporation of results from health studies in air pollution control programs.*** The results of recent studies show evidence of correlations between various types of morbidity and concentrations of air pollutants. Research on health impacts includes effects at the cellular and deoxyribonucleic acid (DNA) levels, chronic lung diseases, different types of cancer, metabolic diseases, neurological effects, concentration-response functions, and the statistical value of life. There is a wide range of studies that provide evidence of the health impacts of air pollutants. However, it is important that these results can be incorporated as support for the design of regulations and programs to reduce air pollution. To do this, the scientific community in Mexico must address the issue of representativeness and robustness of the results, so that they can contribute to the establishment of a scientific basis for the design of air quality control strategies. Furthermore, mechanisms must be created to reduce the gaps for efficient integration of the results of health studies in the design of public policies, including activities for prevention, and the reduction of exposure to pollutants that are harmful to health.

- ***Dissemination of information to reduce exposure***. Another substantial advance has been the real-time dissemination of air quality conditions and their possible impacts on the health of the population of the Megalopolis, based on information from the available atmospheric monitoring networks. The continuous dissemination of information through applications, public reports, news media and social networks helps the population making informed decisions to carry out their activities in indoor and outdoor spaces that reduce exposure to air pollutants, thereby improving people's health and quality of life. These actions have been key before, during and after the declaration of environmental contingencies of O_3 and particulate matter in the Atmospheric Environmental Contingencies Program (PCAA) to alert and inform the population. Information dissemination activities are part of the actions listed in the ProAire for the Megalopolis.

- ***Epidemiological evidence indicates that there is no safe exposure threshold for particulate matter and gaseous pollutants.*** According to the results presented, there is evidence that suggests that the health effects of air pollution are not related to specific limits. The mix of air pollutants in urban areas can be quite complex, and their chemical characterization and health effects present significant challenges. This suggests that exposure to concentrations of particulate matter, even below the WHO air quality guidelines, may be hazardous to the health of the population.

Key science questions

- ***Representativeness of morbidity studies***. A key question refers to the need to better understand the representativeness of the results obtained in morbidity studies, such as metabolic diseases, diabetes, and effects on neurological development, among others. It is important to know if the results obtained in the morbidity studies are robust enough to support the development of new initiatives for public policies and new regulations.

- ***The integration of the results of health studies in the design of public policies***. An issue that must be addressed by the scientific community and decision makers is the establishment of mechanisms to integrate the results of health studies into the public agenda. Beyond the scientific establishment of the relationships between effects on morbidity and exposure to air pollutants, it is vital that the information generated assist in the development of air quality improvement strategies.

- ***Health studies for exposure to other pollutants.*** Traditionally, health studies have focused on criteria pollutants such as O_3 and particulate matter. However, the population in urban areas is typically exposed to complex mixtures of gases and particles. Thus, there is a need to expand studies of the health effects of exposure to chemical mixtures of VOCs, PAHs, toxic pollutants, metals, nanoparticles, emerging pollutants[2], and the complex

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[2] Emerging pollutants, or *pollutants of emerging concern*, are substances of diverse origin and chemical nature that are present in the environment but are not routinely monitored or regulated, which have the

combinations of compounds in particulate matter. These investigations are necessary not only for studies of mortality but also for morbidity.

- ***Exposure studies***. It is necessary to increase and improve our understanding of the characteristics of exposure to air pollutants. This also includes improving the mechanisms to generate the information necessary for exposure studies at the local and regional level. It is important to determine if the results of those studies can be used to improve our understanding of exposure to air pollutants.

- ***Integration of other methodologies***. Improving exposure assessment also involves strengthening collaboration between the agencies that generate the information, as well as integrating other data generation methodologies such as satellite information, personal monitoring, emissions inventories, and air quality modeling. The integration of these methodologies would make it possible to substantially improve the availability of the databases necessary to understand exposure to air pollutants.

Scientific challenges and research needs

- ***Toxicological profiles.*** The results of the toxicological studies show evidence of biological causes and mechanisms that can explain acute, chronic, and trans-generational health impacts. There is, however, the challenge of determining the toxicological profiles of the organic content of particulate matter in different parts of the Megalopolis. It is important to know the regional differences in toxicological profiles to correlate them with specific health impacts for population groups in the Megalopolis.

- ***Impacts due to mixtures of air pollutants and pathogens.*** The study of the health impacts of mixing or combining air pollutants with pathogens (for example, viruses) is still an important challenge that must be addressed by the scientific community. This also includes the need to develop the necessary toxicological methods to address the problem. The complexity of this challenge increases to the extent that the variability of the spatial distributions of pathogens and air pollutants are great within the Megalopolis.

- ***Interaction between climate change, air quality and health.*** There is a complex interaction at multiple scales between climate change and air quality, yet the connection between local air pollution sources and the emissions that drive climate change is very clear. In addition to adverse effects of anthropogenic pollutants on human health, naturally occurring air pollutants such as pollen, biogenic volatile organic compounds, wildfire smoke, and windblown dust may be influenced by climate change and become an increasing health risk. Climate change could also induce changes in the behavior of the population, for example, the time that individuals remain indoors as well as modify the availability and distribution of allergens derived from plants and fungi, this will have effects on asthma and allergic rhinitis in children and adults, consequently, policy

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potential to adversely affect human health and the environment They include personal care or household cleaning products, pesticides, industrial additives, among others.

adjustments and lifestyle changes will need to be addressed to mitigate these harmful effects.

  - When estimating future health effect, in addition to uncertainty in O_3 and PM concentration, there is uncertainty in risk estimates such as modification of the effect due to temperature on the relationships between pollutants and on the human response to the pollutants, altering possible future adaptation resulting from these changes and a potential new risk associated with exposure. It is necessary to begin evaluating the implications of climate change on human health and guide policies towards the mitigation of climate change and air pollution, thus enhancing the health benefits and optimizing resources and costs.

- ***Health surveillance system*.** An interesting proposal is to design and implement a health surveillance system in conjunction with existing environmental monitoring networks in the Megalopolis. The integration of the systems could substantially help the early identification of actions to mitigate exposure to air pollutants, including extraordinary events such as those presented during the COVID-19 pandemic. Furthermore, the proposed integration may help improve the evaluation of the effectiveness of air quality control programs.

- ***Chemical composition of the particulate matter and emerging toxins*.** The associations between the health impacts and the toxicity of the different chemical speciation in the particulate matter should continue and increase, especially for the components of PAHs, metals, and black and organic carbon. This will allow us to understand how chemical aggregation and aerosol formation determine the molecular activation of pathophysiological processes of acute and chronic diseases. It is also necessary to carry out studies of emerging toxic particles such as ultrafine particles, microplastic particles and those that do not derive from combustion such as brake and tire wear, identifying their emission sources and toxic potential.

- ***Methods of health studies*.** To aid in the development of policies to improve air quality, it is necessary to integrate the results of different methods of epidemiological studies such as ecological, case series, cross-sectional studies, case controls, cohort studies, and interventions. For health studies, *in vitro* and *in vivo* models of exposure to toxicants, high-throughput molecular techniques, and physiological function parameters of chronic diseases must also be integrated. It is necessary to advance in the study of the synergistic effects of the urban mix, as well as the effects of emerging pollutants. Exposure models used in epidemiological studies can benefit from the use of data obtained from satellite platforms and low-cost technologies, as well as from the output of numerical model ensembles.

- ***Data on criteria pollutants and other species of interest*.** Data for criteria pollutants with adequate spatial and temporal coverages and resolutions are required for epidemiological and exposure studies. It is necessary to increase the quality of the data to reduce the uncertainty in the evaluations of the impacts. Evaluation of the impacts of emerging pollutants will require the implementation of new technologies in the monitoring networks or in carrying out field campaigns.

- ***Development of management indicators based on the improvement of public health***. Air quality management could benefit from the development and incorporation of health-based indicators that could relate changes in disease incidence or attributed mortality to changes in levels of pollutants such as O_3 and $PM_{2.5}$.

Knowledge gaps:

- In the Mexican context, is there new scientific information on the health effects related to air pollution? What has been the recent information on air pollution and health?
- Is there evidence of chronic and acute effects aggravated by exposure to poor air quality?
- Is there evidence of synergistic effects related to exposure to the various mixtures of pollutants found in different urban environments? Is there sufficient data for its evaluation?
- Is it necessary to develop concentration-response functions suitable for the Mexican population?
- What are the social and economic costs associated with air pollution? Is it necessary to develop methodologies to support cost-benefit evaluations in the entities of the Megalopolis?
- What have been the advances to better estimate the health effects of air quality quantitatively?
- Is there a contribution of outdoor ambient air pollution to indoor exposure?
- What are the thresholds for exposure to particulate and gaseous pollutants? What would be the challenges to achieve them?
- Is it necessary to include any other pollutant or pollutants (for example, ultrafine particles, PAHs) within the ambient air quality regulations?
- How will climate change modify impacts on health?

7.5. Air quality management in the Megalopolis

Much progress has been made in the fight against air pollution problems in Mexico City and in some of the entities of the Megalopolis. However, challenges remain to effectively reduce concentrations of harmful pollutants to protect public health and the environment. Population growth, urban expansion and high motorization of the metropolitan area and the surrounding Megalopolis region will continue to generate polluting emissions. In addition, changes in the urban landscape and climate change have contributed to the progressive increase in temperature in the MCMA and some other entities in the Megalopolis, which could affect local meteorology and air quality. Regional forest fires caused by periods of increasingly frequent and intense droughts induce severe episodes of particle pollution. With the exception of the MCMA, air quality monitoring, emissions inventories, and air pollution studies in the Megalopolis are limited, making it difficult to evaluate regional air quality and the impacts of pollutants in the region necessary to design effective emission reduction strategies.

Knowledge gaps

- How to promote the development of scientific knowledge and promote the creation of research centers outside of Mexico City?
- How does the federal government promote scientific work and capacity development in the entities of the Megalopolis?
- What additional data is needed to design and evaluate the measures of the ProAires of the Megalopolis entities?
- What are the main research needs in each of the urban centers of the Megalopolis?
- The available evidence suggests that the chemistry and physics of the MCMA are changing. How can the government lead a new comprehensive measurement campaign for the Megalopolis?
- What are the scientific lessons learned for environmental management from the restrictions during the COVID-19 pandemic?

Role of CAMe in coordinating regional air quality management

The Megalopolis Environmental Commission (CAMe) was created in 2013 as a coordination body for the planning and execution of policies, programs, projects and actions related to environmental protection, preservation and restoration of the ecological balance, in the region that makes up the Megalopolis of central Mexico.

The CAMe is made up of seven federative entities: Mexico City and the states of Hidalgo, Mexico, Morelos, Querétaro, Puebla and Tlaxcala, and also by four ministries of the federal government: the Ministry of the Environment and Natural Resources (SEMARNAT), the Agrarian, Territorial and Urban Development (SEDATU, *Desarrollo Agrario, Territorial y Urbano*), Infrastructure, Communications and Transportation (*SICT, Infraestructura, Comunicaciones y Transportes*) and HEALTH (SALUD). It has a Government Body, which is made up of the Heads of the federal Secretariats, the Governors of the states and the Head of Government. It also has a Scientific Advisory Committee, made up of fifteen scientists, academics and experts in environmental matters, who have the power to advise and provide their opinions and recommendations on the priority actions of the Commission.

For its operation and functioning, the CAMe has an Executive Coordination, which convenes the sessions of the Governing Body, proposes actions and follows up on the agreements. The Executive Coordinator articulates the actions of eight Working Groups, made up of the technical staff of the entities and institutions participating in the CAMe.

The CAMe has Trust 1490 to support the Environmental Programs, Projects and Actions of the Megalopolis (FIDAM 1490). It receives annual contributions of $5.00 pesos for each vehicle verification carried out in the verification centers of the CAMe entities. FIDAM 1490 can also receive contributions from other sources such as donations, remnants of budget savings from its members, among others.

The CAMe could be strengthened with actions such as the following:

- Include the Ministry of Energy (SENER, *Secretaría de Energía*) and the Ministry of Finance and Public Credit (HACIENDA, *Secretaría de Hacienda y Crédito Público*) of the federal government as members of the Commission, to reinforce the implementation of high-impact regional environmental policies, programs and actions.
- Create an Advisory Council made up of representatives of environmental civil society organizations, and business and service chambers and associations from the environmental sector, where they can give their opinion and follow up on issues of common interest, as well as promote constructive dialogue between environmental authorities. and civil society in general.
- Encourage contributions and donations to FIDAM 1490 from other sources, such as the mandatory vehicular verification of emissions from federal license plate vehicles carried out by the SICT, contributions from the industries with the highest polluting emissions, and strengthening the commitment of the contributions derived from the state vehicle verification.
- Advance in other priority environmental issues in which the CAMe can contribute to harmonizing programs and actions, for example, in the simultaneous and harmonized attention to air quality and climate change, circular economy, water quality issues, waste, mobility and transportation, as well as conservation of Protected Natural Areas, among others.
- Initially, make it a priority to support the promotion of the measures established in the ProAires of the entities to reduce emissions of pollutants in the region's atmospheric basins.
- Promote evidence-based evaluation of the effectiveness of programs and projects in budget decisions and public policies, including the creation of performance requirements in grants and contracts to ensure that programs are executed and meet their objectives effectively.

Air quality monitoring

Although the MCMA has a well-developed air quality monitoring network that covers a large part of the urban area, the spatial coverage of air quality monitoring in the growing metropolitan area of Mexico City and the rest of the Megalopolis is limited. At the Megalopolis level, monitoring is restricted to urban centers. In addition, there is a significant disparity in the quality of the data.

The CAMe has the opportunity to contribute with its management leadership to improve the monitoring conditions of air quality in the Megalopolis. Section 7.1 above lists a series of valuable recommendations that must be managed by CAMe and environmental authorities to improve the quantity, coverage, and quality of data from monitoring networks, highlighting:

- Develop strategic capacities of the Regional Monitoring Network, including different types of sites (urban, peri-urban, rural).
- Provide financial support to improve the infrastructure and technical capabilities of the air quality monitoring network in the Megalopolis, including training in the analysis and validation of satellite data.

Emissions inventories

Emission inventories are an essential air quality management tool for evaluating the progress of emission control strategies and planning future actions. A detailed description of the challenges and recommendations for improving emissions inventories is presented in Chapter 3.

The MCMA emissions inventory is well developed and is used to inform emission reduction strategies. Section 7.2 above described the challenges and opportunities that exist to improve emission inventories in the Megalopolis and that they can be truly useful in air quality management. CAMe can contribute to the implementation of the recommendations listed in Section 7.2 by leading the air quality management process in the Megalopolis. Among the areas of opportunity that can be highlighted include:

- verify inventory objectives and their alignment with management needs,
- improve spatial coverage and resolution,
- review emission profiles and chemical speciation,
- increase the temporal resolution, and
- publish the information of the calculations and uncertainties.

In all cases it is necessary to include or improve the information on the area sources related to the use of solvents in the residential, commercial and service sectors. Specific studies are required to obtain or improve emission factors and activity data, as well as temporal distributions and chemical speciation.

Air quality modeling and forecasting

The Mexico City government has implemented an air quality forecast system to alert the public of high pollution of O_3 and $PM_{2.5}$ 24 hours in advance, and in evaluating emission reduction policies for air quality improvement and other co-benefits. Substantial challenges remain in the implementation of the air quality forecast system in the rest of the Megalopolis due to the lack of data and research to support modeling and forecasting efforts, as well as limited qualified technical personnel.

There are efforts by academic institutions to forecast air quality. The ICAyCC-UNAM has a 72-hour forecast model based on WRF-CHEM for CO, NO_X, O_3, PM_{10} and SO_2 with a spatial coverage that includes Mexico City and neighboring entities, the graphic outputs are available for online consultation. There are other modeling and forecasting efforts in academia and other entities, but the information is not public.

CAMe could provide the financial resources and be a catalyst to develop a system for air quality modeling and forecasting in the entities of the Megalopolis, including collaboration with national and international experts to provide training in air quality modeling and forecasting.

Integrated transportation-land use-air quality management

The uncontrolled urban expansion and the increased motorization in the Megalopolis are major sources of air pollution and congestion. Creating a transport system in proper balance with the environment requires a transversal strategy that integrates the transport sector, changes in land use, air quality management, and that involves the different responsible organizations (environment, transport, urban development, and public works) and with public participation. The goal would be less reliance on individual vehicles through the provision of better public transport and measures that allow for more journeys to be taken on foot or by bicycle. Some of the actions in which the CAMe should take the lead for its implementation include:

- Promote the infrastructure for active or non-motorized mobility.
- Develop public policies for the optimal location of infrastructure and equipment (Compact Cities with mixed land uses).
- Development of inter- and intra-urban mass transport systems (cargo and passengers).
- Orient the urban development of the Megalopolis towards the containment of its expansion (Densification of the Territory).
- More frequent origin-destination studies for infrastructure planning and to improve operations.
- Promote sustainable mobility (teleworking, high-capacity public transport, walking and cycling).
- Establish incentives for the introduction of low-emission vehicles, such as electric and hybrid cars, as well as electric motorcycles.
- Consider limiting the use of private vehicle in heavily trafficked areas.

Atmospheric science

Current observations in the MCMA and other entities in the megalopolis indicate that atmospheric concentrations of pollutants such as O_3 and PM have not decreased to the acceptable limit and have begun to increase in recent years, suggesting the need to update our state of scientific knowledge of the processes that control the formation, transport, and fate of these pollutants. A solid understanding on the changes of the meteorology, emissions and processes that control ozone formation and other secondary pollutants in the MCMA and the megalopolis region is vital in the design of new policy actions. The following describe some of the research needs that the CAMe should promote for the development of air quality management strategies:

- ***Extensive atmospheric measurements and modeling studies*** are needed to define optimal emission control strategies for the particular entity in the megalopolis, considering the local instituional, technical, economic, social, and political circumstances.
  - The application and validation of air quality models requires spatially and temporarily resolved emissions data as well as knowledge of the meteorology and solar radiation. In addition to commonly measured O_3, NO, NO_2, CO, and PM mass, individual VOCs and PM chemical compositions are needed. This detailed information will require special studies to better understand the causes of such emissions and to evaluate progress in reducing them.
  - Policy makers should use this information to balance the economic and social benefits of health improvements against the costs of emission control.

- ***Climate change impacts on air quality and health***. Climate change can impact air quality and, conversely, air quality can impact climate change. Emissions of greenhouse gases (for example, CO_2, N_2O) and short-lived climate forcers (CH_4, BC, O_3) into the air can cause changes in the climate.
    - Improve knowledge of the impacts of climate change on human health and the environment in the Megalopolis region, enhancing enhance the ability of the state and local air quality managers to consider climate change in their decisions to protect air quality and to reduce the impacts of a changing climate, as well as the communities to address climate change effectively and sustainably.
    - Integrate climate change mitigation and emission inventories with air quality management.
    - Quantify the health and economic benefits of reducing emissions of air pollutants and greenhouse gases.
    - Provide tools and resources to develop a more sustainable energy system.
    - Evaluate how different multipollutant/multisector control strategies can affect greenhouse gases and other air pollutant emissions.
    - Develop evidence-based information and resources to inform the public and the communities to better prepare about potential climate threats created by wildfires, floods, droughts, and other extreme events, particularly on the most vulnerable populations.

Impacts of air pollution

Air pollution adversely affects human health, causes regional haze and acid deposition, damages crops and the ecosystems. Most studies in Mexico have focused on understanding the impacts of air pollutants on human health. There are information gaps about the impacts on crops, forests, ecosystems and cultural heritage and public and private infrastructure. Policies and programs for air quality control in the Megalopolis have incorporated some of the results of health studies on particulate matter and O_3. However, key questions and issues remain about the relationship between chronic and acute health effects that are aggravated by exposure to poor air quality and the quantification of the health costs and benefits of controlling key emission sources. Below are some of the research needs that CAMe should promote for the development of programs that improve the estimation of these impacts.

- Provide sufficient resources for research on air pollution and health.
- Generate standards for other environmental toxins of interest to the region, for example, benzene, polyaromatic hydrocarbons, among others.
- Carry out more studies on particle composition to estimate their health risks.
- Strengthen and improve air pollution and health surveillance systems.
- Strengthen studies on the impacts and benefits of air quality management programs on health.

- Generate scientific knowledge about the impacts of air pollution on ecosystem, forests, vegetation and crops
- Generate evidence on the effects of acid rain on crops, bodies of water, cultural heritage, and public and private infrastructure.

Communication, capacity development and stakeholder engagement

The success and sustainability of environmental policies depend on high levels of citizen awareness and the informed participation of interested parties. Permanent changes in the attitudes and behavior of the population require the development of an environmental culture and improvements in education. Many policies will not work unless stakeholders take ownership of them and share responsibility for their implementation. Their participation can provide support for unpopular but cost-effective measures taken in the public interest, especially if these measures are transparent to the population. It is essential to improve the capacity of human resources necessary to diagnose environmental problems, as well as to formulate, execute and evaluate policies and programs aimed at improving air quality. More trained personnel will improve the performance of the government, the private and academic sectors, and non-governmental organizations. CAMe should be a leader in air quality management by promoting the implementation of the following recommendations:

- Support the ongoing educational activities of the Megalopolis entities aimed at raising environmental awareness among the general public.
- Allocate financial resources for environmental education programs.
- Support air pollution research at universities and government institutions to strengthen environmental management capacity in federal, state, and local government agencies, as well as in the industrial and academic sectors.
- Develop evidence-based information and resources to improve communication with the public and communities so they can be better prepared for potential climate threats created by wildfires, floods, droughts and other extreme events, particularly among the most vulnerable populations.
- Involve stakeholders and the general public in the design and implementation of emissions reduction strategies, including the development of information campaigns on the benefits of reducing emissions for the population.
- Involve communities and non-governmental groups in monitoring and detection studies of high pollution areas through the use of low-cost sensors.

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