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

Executive Summary

Molina Center for
Energy and the Environment

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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.

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 3 million inhabitants in 1950 to more than 18 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 59 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.

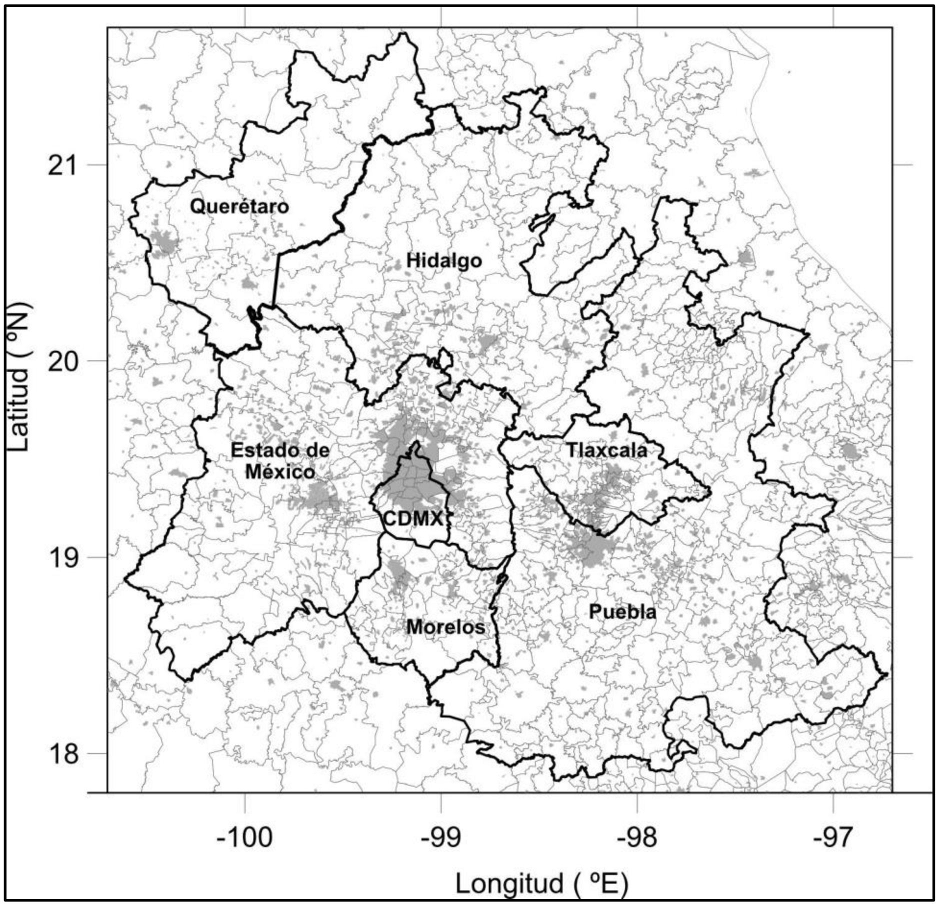

Figure 1. Map of the Megalopolis, the state limits are indicated with a thick black line, while the municipal ones with thinner lines, the urbanized areas are highlighted with a gray shading.

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.

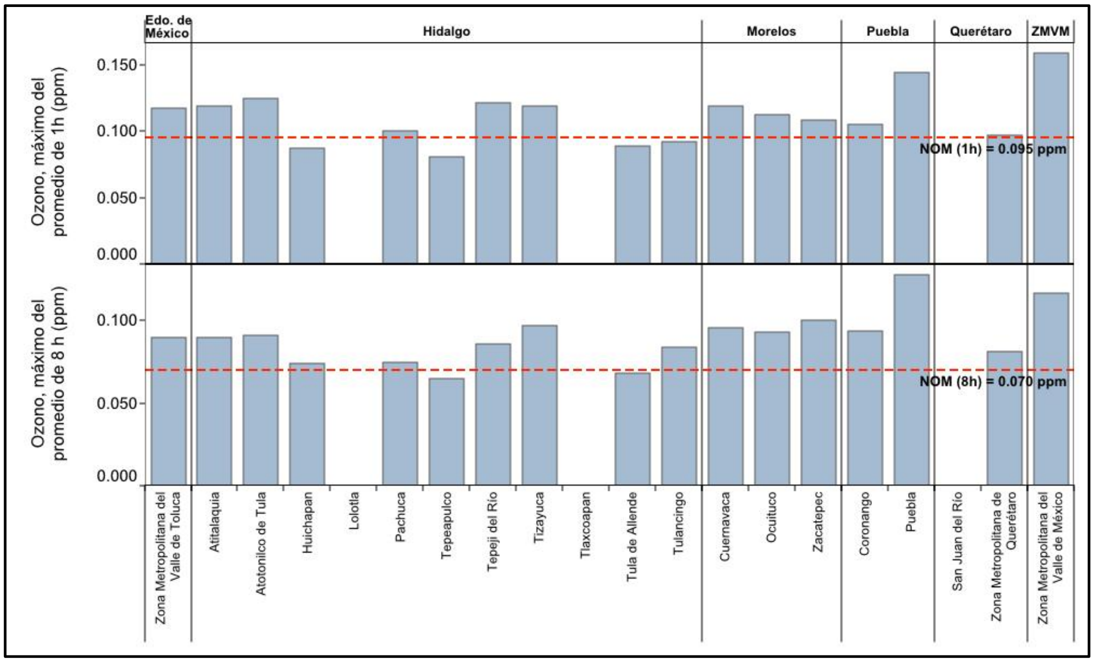

Figure 2. Comparison of the maximum O_3 concentrations for the 1-hour (upper) and 8-hour (lower) average reported by the different monitoring networks in the Megalopolis region during 2020. The limit values of NOM-020-SSA1-2021 are indicated with the dashed red line (Source: prepared with data from INECC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

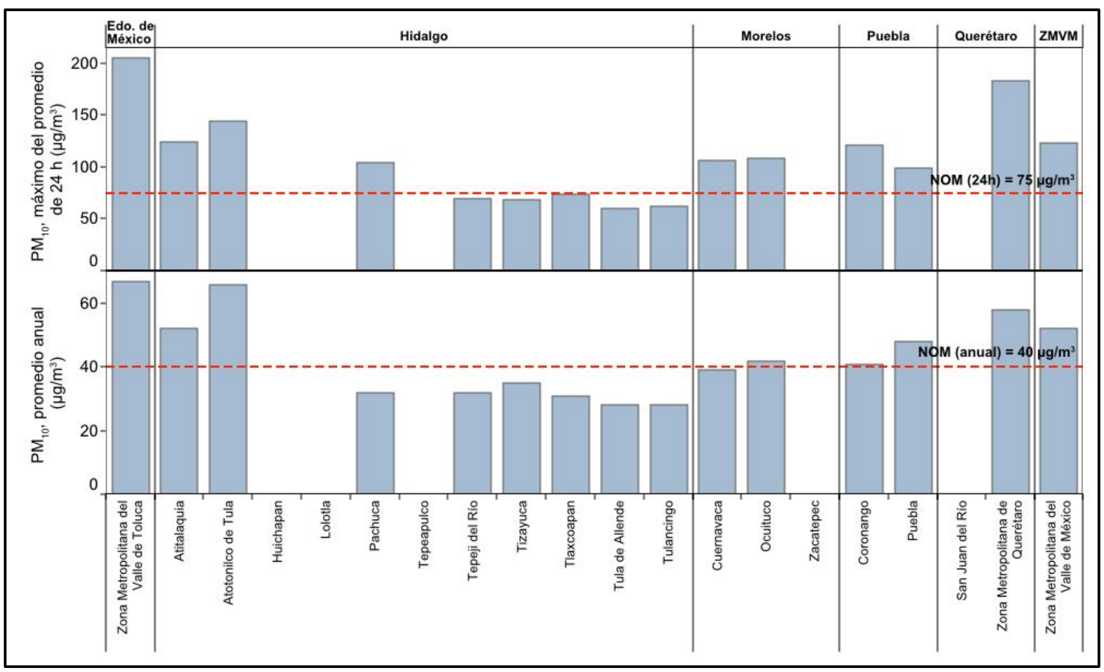

Figure 3. Comparison of the maximum PM_{10} concentrations for the 24-hour (upper) and annual (lower) average reported by the different monitoring networks in the Megalopolis region during 2020. The limit values of NOM-025-SSA1-2021 are indicated with the dashed red line (Source: prepared with data from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

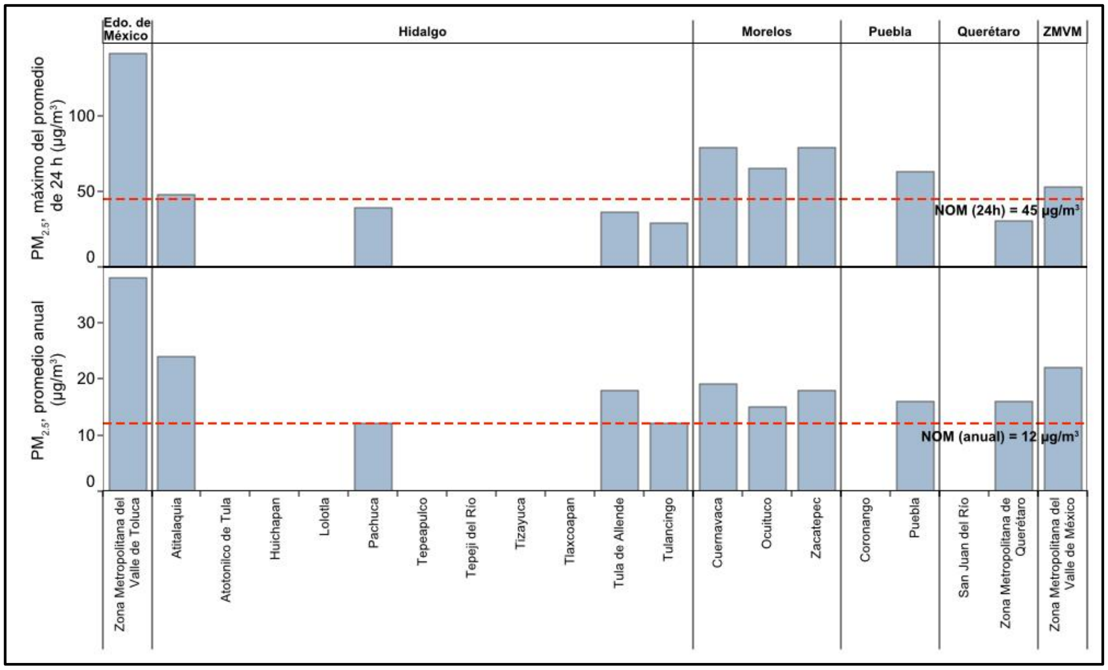

Figure 4. Comparison of the maximum $PM_{2.5}$ concentrations for the 24-hour average (upper) and annual average (lower) reported by the different monitoring networks in the Megalopolis region during 2020. NOM-025 limit values -SSA1-2021 are indicated with the dashed red line (Source: prepared with data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

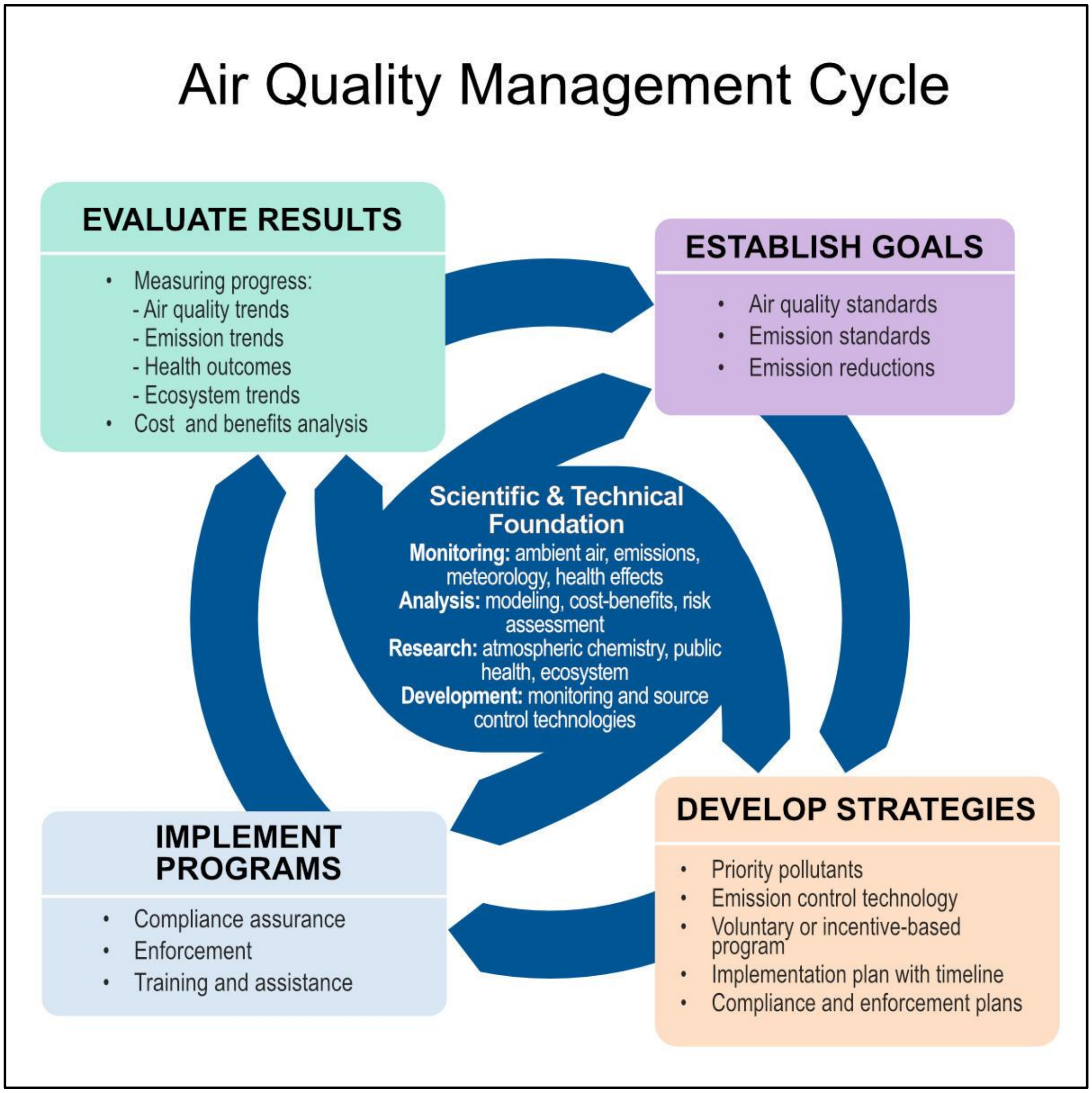

Figure 5. The air quality management process (Adapted from NRC, 2004 and Bachman, 2007).

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 32 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, that 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.

- ***Measurement of emissions of VOCs and toxic organic compounds.*** 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.

  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 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?

<u>Impacts of Tula-Tepeji industrial corridor on the air quality of the MCMA and the Megalopolis region</u>

- 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.

<u>Air quality modeling and forecasting</u>

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

<u>**Lessons learned**</u>

- ***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 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 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.

Impacts of air pollution

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.