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Mexico City air quality: a qualitative review of gas and aerosol measurements (1960–2000)

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Abstract

Mexico City, one of the largest cities in the world, has a major problem with high levels of anthropogenic gases and aerosols. Some facets of this problem have been studied through measurements made during the past 40 years. These measurements are reviewed and evaluated with respect to physical processes that underlie the primary and secondary formation of gases and aerosols, their spatial and temporal evolution as well as their potential impact on the local and regional environment. Past measurements are heavily biased towards certain locations and time periods, and are of limited use for understanding fundamental processes that govern the formation and evolution of the principal pollutants. Recommendations are made whereby the measurement database could be expanded to better represent the characteristics of Mexico City gases and aerosols and to contribute to mitigation strategies that would lessen the environmental impact of these pollutants.

Keywords: Ambient gas and aerosol measurements; Air pollution; Mexico City

1. Introduction

Urban areas produce complex varieties and quantities of gas and particle species whose characteristics depend on a range of factors, including population density, energy consumption, industrial processes, and modes of transportation and usage. These pollutants affect public health, damage agriculture, and alter weather and climate. Many studies have been conducted over the years to better quantify the components of the urban pollution problem, i.e. to identify the sources and magnitudes of pollution and assess its subsequent impact. The majority of these studies were conducted in the United States and Europe where regulations have been implemented to restrict the emission of pollutants. Global "*megacities*" in developing countries differ in a number of ways from cities that have been studied in the US and Europe. Less strict regulations allow the production of higher levels and more complex (and possibly more toxic) gases and aerosols. A large fraction of megacities outside of Europe and the US are located in sub-tropical and tropical latitudes where the meteorology and chemistry is quite different than in mid-latitudes. Solar irradiance is higher, winds are lighter and removal processes differ. Another important feature of the megacities in developing countries is the persistence of urban–rural transition zones with unpaved areas, agriculture, cattle, deforested zones, lack of sanitary infrastructure, etc. This close coexistence of rural and urban environments is an important factor that is often overlooked when assessing pollution problems in developing nations. Certainly other polluted cities such as Sao Paulo in Brazil and to a lesser extent, Santiago in Chile, suffer many of the same problems as Mexico City (Kretzschmar, 1994; Cahill et al., 1996).

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Mexico City is a tropical megacity, but unlike many such cities, its pollution problem has been studied for more than 40 years. A moderate set of measurements from these studies have been reported in the open literature while others can be obtained from internal reports. From these we can learn something about underlying physical processes that govern the evolution of those contaminants most harmful to the environment.

The populations of cities continue to increase as well as the amount of pollution produced. According to studies by the United Nation (WHO/UNEP, 1992) more than 50% of the world's population resides in urban areas with an expected increase of 15–20% in the next 30 years. Studies such as those that have been conducted in Mexico City provide valuable information that can provide insight into similar problems in other megacities. The present paper provides a summary of these studies, evaluates their content with respect to some of the principle scientific questions associated with air quality and identifies where additional measurements are needed.

2. Evaluation methodology

The studies of Mexico City air quality involve measurements and modeling of anthropogenic gases and aerosols; however, this paper will only review the observational studies. The purpose of this review is to identify where insufficient data exist to adequately investigate the fundamental physics that govern the production and evolution of gases and aerosols in Mexico City. These processes are complex, involve many chemical reactions and interactions with gaseous and particulate species and are dependent upon meteorology and radiation. We have chosen four general processes to assess the content of the published studies: (1) primary and (2) secondary production of gases, (3) primary and (4) secondary production of aerosols. In addition, we assess how well the measurements represent spatial and temporal variability.

Atmospheric pollution in Mexico City has been a significant problem for more than two decades due to the unrestricted growth of population and industry. The photochemical smog combined with high levels of primary particles is the result of emissions by vehicles (about 3.4 million), industry and two thermoelectric plants located within the elevated basin (2.2 km above sea level), as discussed in PROAIRE (1996). The variation with location, time of the day and time of the year can be seen in a statistical analysis of measurements from the city's pollution monitoring network, Red Automática de Monitoreo Atmosférico (RAMA). This network, established in 1986, now consists of 32 stations that measure CO, O_3, NO_x, SO_2, PM-10, temperature, relative humidity and winds. Not every station measures all these variables, but all of these variables are measured by at least one station in the central, NE, NW, SE and SW sectors of the city (Fig. 1). The daily, average maximum values of carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2) and PM-10 data are shown in Fig. 2, where the four traces in each panel represent measurements from the NE and SW sectors of the city. Figs. 3 and 4 present monthly and yearly averages in the same format as Fig. 2. The general trends are similar but the differences in relative magnitude suggest that the emission and secondary production rates probably vary from sector to sector in the city. The large diurnal and monthly variations also underscore the trends that are likely a result of meteorology, traffic patterns or other factors that affect dispersion of emissions.

Mexico City has taken steps in the past 10 years to address its pollution problem. Table 1 is a chronological history of the different measures that have been implemented. As seen in Fig. 4, CO and SO_2 are decreasing since 1991 when the most significant measures were implemented. Ozone, however, shows no obvious signs of diminishing. The effect of emission reduction strategies on PM-10 cannot be assessed with the RAMA measurements as automatic monitoring of particles was only implemented in 1993. The major difference in CO and SO_2, coupled with the lack of change in O_3, underscores the need to compare measurement studies before and after 1991 to better understand why pollution mitigation strategies have failed to lower ozone levels.

Studies in other large cities, e.g., Los Angeles, have shown that deterioration of air quality can be attributed to primary emissions of gases and particles, followed by secondary production through photochemical processes. The primary gases that are emitted are CO, NO, SO_2 and unburned hydrocarbons. The primary particles emitted are soot, which may contain large significant concentrations of volatile organic compounds (VOCs) formed during combustion of hydrocarbons. Ozone and a large variety of organic compounds are formed through secondary, photochemical reactions. In the absence of VOCs, ozone and NO_x exist in a state of equilibrium during daylight hours whereby NO reacts with O_3 to produce NO and NO_2 is converted back to NO as a result of photolysis, which also leads to the regeneration of O_3 (Seinfeld and Pandis, 1998). In the presence of VOCs, however, excess O_3 is produced because of the removal of NO by organic peroxy radicals (RO_2) that are produced from the photochemical oxidation of VOCs. For this reason, in addition to measurements of NO_x and O_3, there must be measurements of VOCs and RO_2 if we are to understand the processes that produce O_3.

A large fraction of the aerosol population is produced from homogeneous and heterogeneous nucleation, and

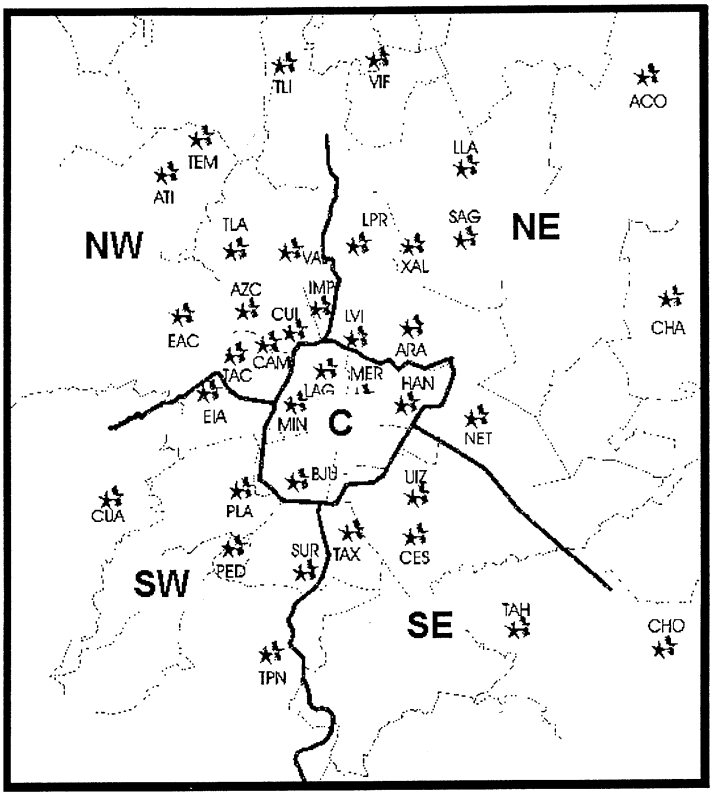

Fig. 1. Map of Mexico City's Metropolitan Region, divided into five sectors for monitoring purposes by Red Automática de Monitoreo Atmosférico (RAMA). The stars show the location of the monitoring stations, with the three-letter acronym that identifies each station.

then grows by condensation and coagulation. These processes can only be understood if size differentiated measurements are made of the chemical composition of these particles. As is well known, aerosols have size distributions that are characterized by three peaks: the nucleation, accumulation, and coarse modes, respectively. The sizes where these modes appear are different for size distributions of number and mass concentration, and will depend upon the composition of the aerosols and the associated environmental conditions. The characteristics of these size distributions provide important information on how the aerosols form and evolve and what their potential impact will be on health and the environment.

The remainder of this presentation will summarize the measurement studies that have been conducted since 1960 and will stratify them according to location, time and the species measured. The principal conclusions that came from these studies are elucidated, followed by a discussion that places these measurements in the context of understanding the processes that govern the primary and secondary production of gases and particles in Mexico City.

3. Gas measurements

There are numerous studies that discuss measurements of gases resulting from anthropogenic activities over the past 40 years. Prior to 1986 when the RAMA was initiated, studies focused primarily on emissions from combustion sources, while more recently, the focus has shifted toward measurements of photochemical pollutants and organic compounds. Table 2 presents a summary of the studies that discuss different aspects of these gases, starting in 1960. Studies can be grouped into those that make their own measurements (Table 2, ref. # 1–3, 5–8, 10–19, 23, 25, 26, 29–31) and those that analyze data from RAMA stations (Table 2, ref. #. 4, 9, 20–22, 24, 27, 28).

3.1. *CO, CO_2, SO_2, NO_x, and O_3*

The main conclusions from the papers that discuss these gases can be summarized as follows:

- (Table 2, ref. # 1, 4, 6, 11, 22, 27, 28) Trends in CO, NO_x and SO_2 are dominated by two daily peaks at

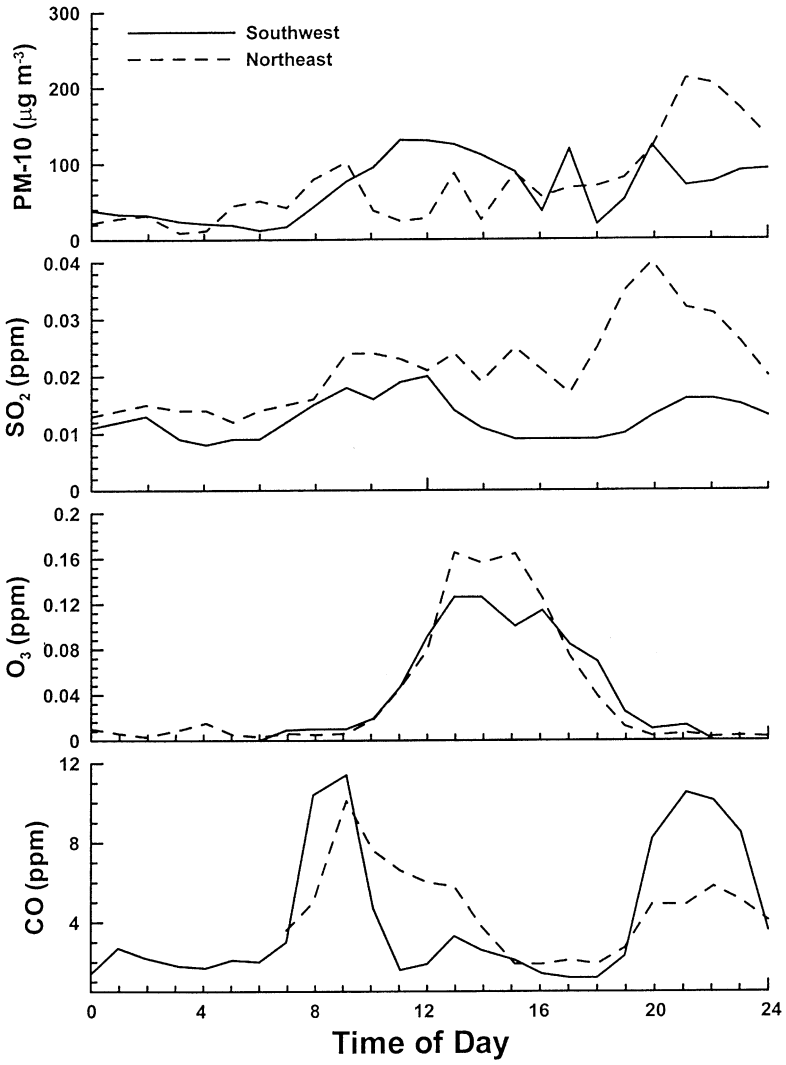

Fig. 2. Time series of PM-10 (top panel), SO_2, O_3 and CO (bottom panel), presenting the hourly average concentrations at two different monitoring stations.

the morning and afternoon rush hours, and a single O_3 peak in the early afternoon.

- (Table 2, ref. # 2) Diurnal trends in CO_2 present three peaks: morning, mid-afternoon and evening.
- (Table 2, ref. # 5, 6, 11, 20, 21, 24, 28, 31) O_3 concentrations increased sharply in 1986 and have only decreased by 20% since 1991.
- (Table 2, ref. # 1, 2, 4, 11) O_3, CO_2 and SO_2 present lower average concentrations during the wet season (May–October).
- (Table 2, ref. # 6) Traffic on primary arteries contributes a significant fraction to the total emissions produced by internal combustion engines.
- (Table 2, ref. # 6, 9, 16) Commuters in public transport are exposed to CO levels well above those in other cities of the world.
- (Table 2, ref. # 6, 13, 17) 1% of the vehicle fleet sampled in 1991 show that average CO emissions are high compared to the US fleet, but more comparable in HC emissions. A possible significant contribution of HC from industry was also noted.
- (Table 2, ref. # 11, 13) Airborne measurements provided vertical profiles of O_3, NO_x, CO and aerosols. Pronounced peaks in O_3 and aerosol concentrations were observed at the top of the mixed layer during the morning hours and decreased during the day.
- (Table 2, ref. # 11) Lidar and tethersonde measurements confirmed these results and showed that the O_3 persisted as an elevated layer at about 1 km throughout the night.

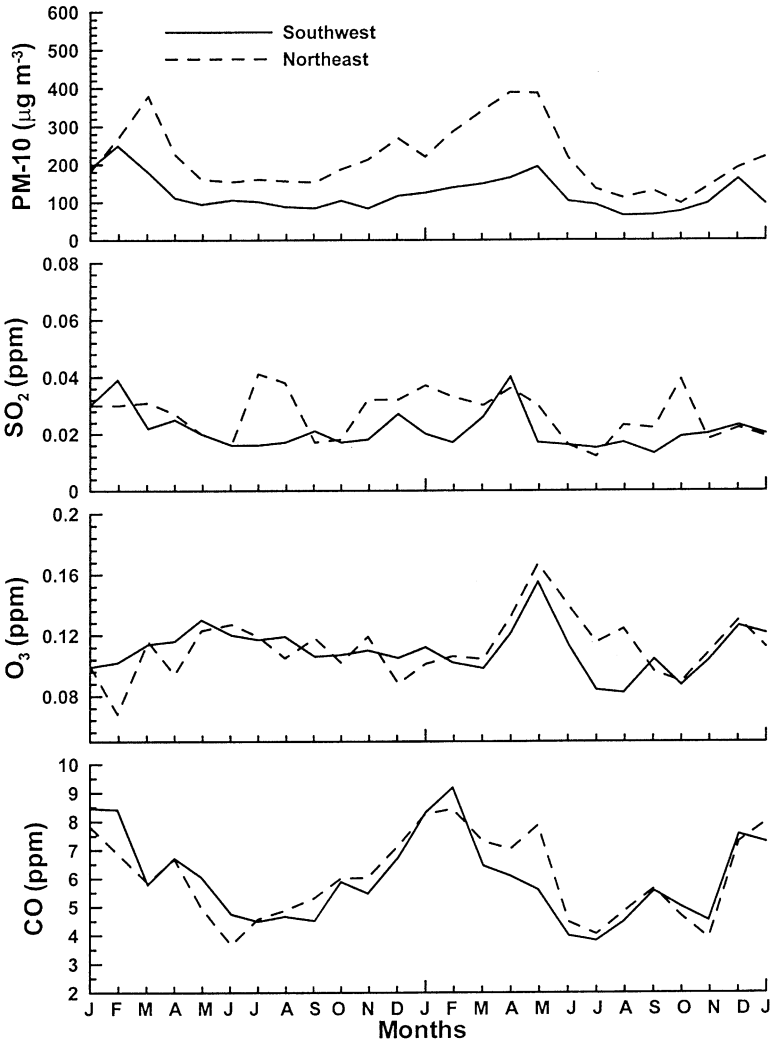

Fig. 3. Time series of PM-10 (top panel), SO_2, O_3 and CO (bottom panel), presenting the monthly average concentrations at two different monitoring stations.

- (Table 2, ref. # 15) The contribution of ozone to the total column in the urban area of Mexico City is about 20 DU.
- (Table 2, ref. # 18) Direct measurements of NO_2 photolysis rates in Mexico City, using a flow reactor, show the importance of providing local resolution for photolysis rate by considering different local conditions and a better characterization of aerosols properties.

3.2. Hydrocarbons and volatile organic compounds

The main conclusions of the papers discussing hydrocarbons (Table 2, ref. # 6, 8, 10, 12, 13, 17, 21, 23, 26, 29) and organic compounds (Table 2, ref. # 3, 12, 13, 19, 25, 30) can be summarized as follows:

- (Table 2, ref. # 12, 13) The ratio of non-methane hydrocarbons to NO_x in Mexico City is larger than 20.
- (Table 2, ref. # 23, 25, 26, 29) The concentration of more than 200 identified hydrocarbons decreases significantly from north to south and the ambient composition showed 56% alkanes, 17% aromatics, 11% alkenes and 4% alkynes.
- (Table 2, ref. # 3, 12, 14, 19) Measurements of formaldehyde and acetaldehyde showed no significant variation between monthly mean values and are among the highest reported in the literature—similar

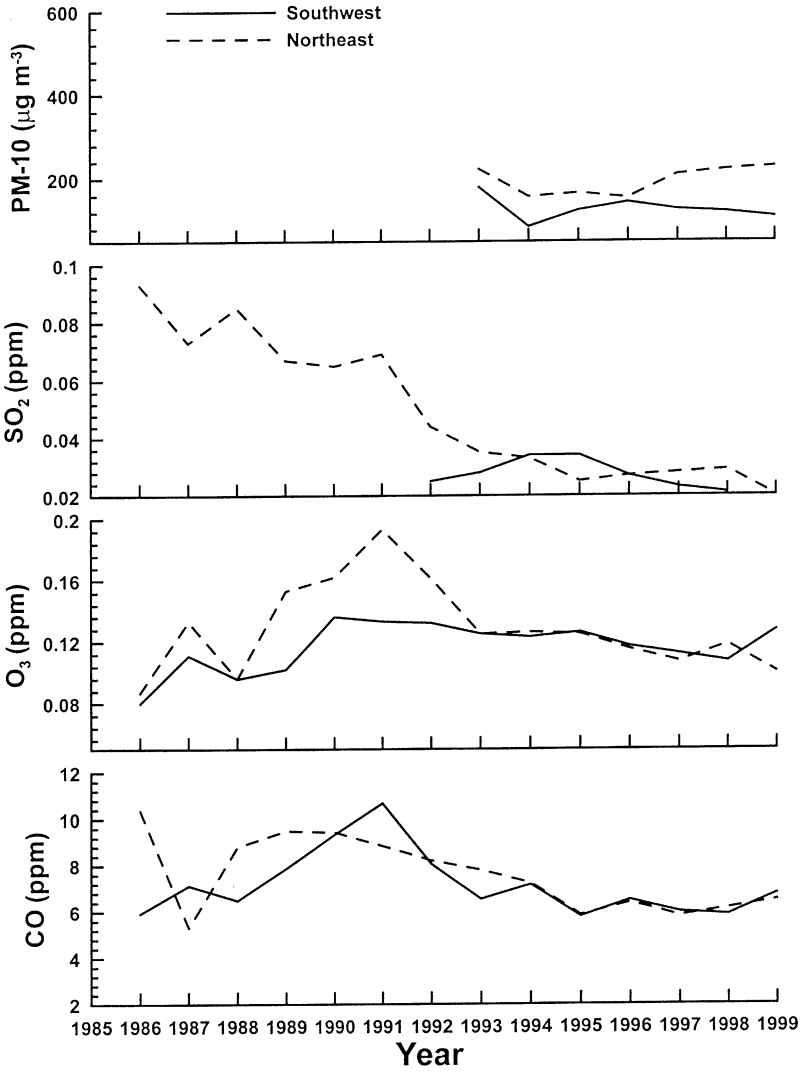

Fig. 4. Time series of PM-10 (top panel), SO_2, O_3 and CO (bottom panel), presenting the yearly average concentrations at two different monitoring stations.

to those measured for Los Angeles during severe photochemical pollution conditions in the 1960s and 1970s.

- (Table 2, ref. # 3, 12, 14, 19) Formaldehyde levels were consistently higher than those of acetaldehyde during the sampling period and the highest levels of carbonyl compounds were found in the morning hours. Formaldehyde was higher during sunny days, but acetaldehyde showed no difference.
- (Table 2, ref. # 3) Formaldehyde mixing ratios in rainwater are very high. Scavenging by rainfall below cloud base is more active during the earlier portions of rain development.
- (Table 2, ref. # 30) Peroxyacyl nitrates (PANs) were very high, purportedly the highest ever reported in the US. A very strong diurnal variation was observed, with maximum concentrations during the early afternoon. It is likely that the introduction of MTBE in gasolines in the 1990s has contributed to the high levels of isobutene and formaldehyde observed in ambient air.
- (Table 2, ref. # 8) Natural hydrocarbons may represent between 10% and 25% of the total hydrocarbon emissions within the basin.

4. Aerosol measurements

Different samplers are used to determine the concentration of particulate matter and the subsequent analysis

Table 1
Air pollution mitigation measures

Year	Type of action taken
1986	Partial introduction of natural gas in power plants and some industries
1986	RAMA begins making measurements to monitor air quality
1987	PEMEX[a] begins program to gradually remove lead from gasoline
1988–1989	A group of non-government environmental scientists initiates a program "Hoy No Circula" in which motorists are asked to voluntarily not drive 1 day each week
1988–1989	A pilot program is initiated to inspect and maintain private vehicles
1990	The federal government officially acknowledges that there is an air quality problem in Mexico City and launches a plan whose principal components were (1) introduction of gas without lead and diesel with lower SO_2, (2) oxygenated compounds in gasoline, (3) SO_2 emissions control in the oil refineries, (4) control of evaporative emissions in storage facilities for combustible liquids, (5) implementation of a mandatory "Hoy No Circula", (6) use of liquid petroleum (LP) in commercial vehicles, (7) use of natural gas in power plants, and (8) mandatory, yearly inspections of all vehicles registered in the city
1991	Replacement of older public buses with newer minibuses with catalytic converters begins

[a] Petróleos Mexicanos (PEMEX), the Mexican national oil company.

of the mass in the exposed filters provides information on their composition. Total suspended particles (TSP) were sampled using high volume (HV) samplers, while stacked filter units (SFU) were used to separate particles into two size categories: 2.5–15 μm (coarse fraction) and less than 2.5 μm (fine fraction). Some studies used HV samplers for PM10 and PM2.5 and cascade impactors were used in other studies to determine mass size distributions in a range of sizes, depending on the number of stages.

4.1. Composition

The majority of the particle composition utilized elemental analyses, based on the following techniques: proton induced X-ray emission (PIXE), proton elastic scattering analysis (PESA) and laser integrating plate method (LIPM). Eleven papers (published between 1984 and 2000) present elemental composition of TSP, coarse and fine fraction determined from PIXE and PESA analyses and sampled at different locations throughout the city over different sampling periods (see Table 3a, ref. # 3, 6, 7, 9, 10, 12, 15, 16, 17, 19 and 21). Several of the studies used other techniques or multiple techniques to determine composition, as also listed in Table 3a (ref. # 1, 4, 8, 14, 18 and 20). Only four studies (Table 3a, ref. # 2, 5, 11 and 18) report mass size distributions and two of them provide information on composition as a function of particle size.

The main conclusions with respect to the elemental composition can be summarized as follows:

- *TSP*. The highest diurnal concentrations are observed between 6 a.m. and noon, with a tendency for maximum concentrations in the winter season (for 23 elements from sodium to lead).
- *Coarse and fine fractions*. Fine mass concentrations of sulfur are more abundant than coarse mass concentrations. Day versus night variability, for metals such as copper, zinc and lead shows that they are present at all times, indicative of uninterrupted industrial activity. Daytime samples show higher concentrations during the rainy period, while dry season concentrations show no difference between day and night. Three dominant sources are identified for the measured elements in the fine mass: (a) ammonium sulfate or sulfuric acid; (b) automotive emissions; (c) industrial emissions. In contrast, the coarse mass shows soil as their principal components, with also some contribution from industrial and vehicle sources. Even though lead concentrations in PM-10 samples have decreased in concentration with time, high lead levels were found in the blood samples of children and women living close to the sites where airborne particles were sampled.

Regarding ionic composition, mineral content, organic carbon and black carbon content of particles, the conclusions are as follows:

- *TSP*. (Table 3a, ref. # 1, 4, 8) Maximum concentrations of sulfates and nitrates occur during the dry season. Minerals composed primarily of quartz, tridimite, cristobalite, feldspar, calcite and iron oxides constitute 25% of TSP mass. The fraction of organics soluble in benzene, presents maximum concentrations in December and January and minimum concentrations during June–August.
- *Coarse fraction and fine fractions*. (Table 3a, ref. # 8, 20) PM-2.5 mass is highest in the northern and Eastern parts of Mexico City. Secondary ammonium nitrate and ammonium sulfate were distributed homogeneously and constituted 10–20% of PM-10 and 15–30% of PM-2.5. Carbon containing aerosols accounted for 20–35% of PM-10 and 25–50% of PM-2.5.

Table 2
Gas measurement summary

	Reference	Species	Technique	Sites	Measurement dates
1	Bravo (1960)	Particles	High volume sampler (fine fiber glass filter)	S, NW	Sep. 1959
		Smoke	Smoke sampler (filter paper)		Dec. 1959
		SO_2	Fluorescent SO_2 analyzer		Jan.–Jul. 1959 (6 months)
2	Báez et al. (1988)	CO_2	GC	S, NW, C	1981–1982
3	Báez et al. (1989)	Aldehydes and ketones	Visible spectroscopy	SW	Jul.—Dec. 1985
4	Bravo et al. (1990)	SO_2	Fluorescent SO_2 analyzer	RAMA	1986–1988
5	Garcia et al. (1991)	O_3	Chemoluminescence	SW	1985, 1987–1998
6	Beaton et al. (1992), Tejeda and Aquino (1993), MARI (1994), Streit and Guzmán (1996)	CO, CO_2 and HC	FEAT unit (collimated infrared light, detector with specific filter for CO, CO_2 and HC)	Vehicular fleet (32,000 vehicles), N, SE, SW	Feb. 1991
7	Nickerson et al. (1992, 1993), Perez Vidal and Raga (1998)	SO_2, O_3, CO	Fluorescent SO_2 analyzer, Chemoluminescence O_3 analyser, GFC	Research aircraft over entire city, airport soundings	13 and 19, Feb. 1991
8	Ruiz-Suárez et al. (1993)	Natural HCs	Experimental emission factor	All sectors	Prior to 1993
9	González et al. (1993)	CO	GFC	RAMA	Jan., Apr., July, Oct. 1988–1990
10	Seila and Lonneman (1993)	HC	GC	All sectors	Mar. 1992
11	Streit and Guzmán (1993, 1996), MARI (1994)	O_3, SO_2, NO_x	Tethersonde and ozonesonde Chemoluminescence	SE, NE	Sep. 1990 (2 weeks)
12	MARI (1994)	HC, aldehydes and ketones	GC/GC–MS and portable photoionization monitor, HPLC	All sectors	Feb. 1991, Mar. 1992,1993
13	MARI (1994) Streit and Guzmán (1996),	CO, CH_4, NMHC and speciated HC	Portable photoionization detector and canisters	NW, SE, SW	Feb. 11–Feb. 21, 1991
14	Báez et al. (1995a, b)	Aldehydes and ketones	HPLC	SW	Mar.–May 1993
15	Juárez et al. (1995)	Ozone column	Dobson's spectrophotometer	SW	1986–1989
16	Fernádez and Ashore (1995)	CO	Infrared absorption	Inside motor vehicles	Mid-Jan. and Mid-Mar. 1991
17	Blake and Rowland (1995)	HC	GC	NE, C, SW	Feb. 1993
18	Castro et al. (1995, 1997)	NO_x	Chemoluminescence	NW, C, SW	Feb., Mar., Apr. 1994
19	Báez and Belmont (1996)	Aldehydes and ketones	Visible spectroscopy and HPLC	SW	Jun.–Sep. 1982, 1983
20	Nava et al. (1996)	O_3	Chemoluminescence	RAMA	Winter/spring 1987–1994
21	Riveros (1996)	O_3, NO_x, HC (benzene, toluene, formaldehyde, *p*-xylene)	Chemoluminescence, canister analysis	RAMA	Dec. 28–31, 1992 Mar. 1–15, 1993
22	Raga and LeMoyne (1996)	O_3, SO_2	Chemoluminescence Fluorescent SO_2 analyzer	All sectors RAMA	1993
23	Arriaga et al. (1996, 1997a, b)	HC	GC	All sectors	Mar., Nov., 1992–1996
24	Nava et al. (1997)	O_3	Chemoluminescence	RAMA	Jan.–Feb., Apr. –May. 1988–1996
25	Ruiz-Suárez and Andraca-Ayala (1997)	Aldehydes and ketones	HPLC	SW, NW	Jan.–Mar., 1996
26	Arriaga et al. (1997b)	HC	GC	C	Feb.–Mar. 1997

Table 2 (*continued*)

	Reference	Species	Technique	Sites	Measurement dates
27	Riveros et al. (1998a)	CO	GFC	RAMA	1987–1995
28	Riveros et al. (1998b)	O_3, NO_x, SO_2 and CO	Chemoluminescence and GFC, canisters GFC	RAMA	Mar. 1992
29	Mugica et al. (1998) Gamas et al. (1999)	HC	GC	All sectors	May, 1996
30	Gaffney et al. (1999)	Peroxyacyl nitrates	GC	NE	Feb.–Mar. 1997
31	Bravo and Torres (2000)	O_3, reformulated gasoline	Chemoluminescence	SW	Jul. 27– Aug. 2 1998

- *Size distributions*. (Table 3a, ref. # 5, 11, 18) Measurements have only been made in the SW, at the university campus and 400 m above the average city level. The fine fraction (defined as particles with aerodynamic diameter between 0.49 and 3 μm) constituted between 40% and 60% of the total mass from 32 samples throughout the year, and shows a seasonal pattern of somewhat lower concentration of the fine fraction during the rainy months. CCN and Aitken nuclei are correlated with vehicular and industrial activities. High resolution, time-dependent size distributions show a clear diurnal pattern, related to the development and growth of the polluted layer, as well as to the local meteorology. The presence of sulfates in small particles has been linked to volcanic emissions and to increased efficiency of gas to particle conversion in cloudy and rainy conditions.

A separate category of particles is considered to discuss the results of biological measurements regarding both free organisms in the atmosphere (as particles) and the biogenic elements associated to airborne particles. Bacteria, fungi, algae and protozoa, as well as proteins, carbohydrates and other biogenic compounds, have been sampled, classified and counted in several studies. Work has also been done on the characterization of biological airborne material, their viability and those characteristics that could be used as environmental quality indicators. These types of aerosols can cover a size range from less than 1 μm to greater than 30 μm. Table 3b presents the details of these studies.

The main conclusions for the different types of bioaerosols can be summarized as follows:

- *Bacteria*. (Table 3b, ref. # 7, 11) A great heterogeneity in viable bacteria abundance (from 14 to 13 000 CFU m^{-3}) showed larger amounts during the dry season coinciding with the pattern observed for PM_{10}.
- *Algae*. (Table 3b, ref. # 1, 2) Ten species were identified and variations in algal counts were related with wind speed and direction, with maximum variety observed during the dry season.
- *Fungi*. (Table 3b, ref. # 4, 5, 8, 10) Total fungal colonies present the highest average concentration at night and the lowest at noon without a definite seasonal trend. In contrast, *Aspergillus* (14 species isolated) presents a seasonal pattern with maximum concentrations in the dry season and more abundance in morning samples. Eight species of *Penicillium* were observed, but no seasonality was present. Basidiomycete spores constitute 32% and 28% of the total airborne fungal spore load in south and central areas, respectively. The largest concentrations are observed in the wet season and greatest abundance in the early morning (2:00–6:00 h). Deuteromycete conidia constitute 52% of the spores trapped in the SW and 65% in the Central area and its abundance is correlated with maximum temperature and relative humidity of the previous day.
- *Protozoa*. (Table 3b, ref. # 3, 6) Out of 63 strains of protozoa belonging to 18 free-living species of flagellates, amoeboflagellates and ciliates that were isolated, the highest diversity was recorded in the NE and NW. Species of the genera *Bodo*, *Monas*, *Cercobodo* and *Colpoda* were the most abundant, and all species isolated were small and cyst formers.
- *Proteins*. (Table 3b, ref. # 9) Protein presence does not show a geographical pattern but has a clear seasonal one, with highest concentrations in the dry season positively correlated with airborne PM10.

4.2. Optical properties

Aerosol optical properties (combining their size and composition) have a direct impact on atmospheric visibility, particularly in regions of high pollution. Table 3c lists the details of the studies that have been carried out linking radiation measurements to aerosol pollution in Mexico City. The main conclusions can be summarized as follows.

- No correlation is found between TSP and visibility, but a significant one exists between fine particles and visibility. Particles with diameters in the range

Table 3

	Reference	Aerosol property measured	Instrumentation and sample rate	Analysis technique	Location	Measurement dates
(a) Non-biogenic particle measurement summary						
1	Salazar et al. (1981), Bravo and Salazar (1982, 1984), Salazar and Bravo (1986), Salazar et al. (1989)	TSP; mineral, metals and soluble organics, SO_4^{2-}, NO_3^-	Hi-vol, 24 h samples	Gravimetric; XRF for soil elements; organics extracted with benzene and ion chromatography	SW	7/79–8/80 (179 days)
2	Bravo et al. (1982)	TSP and FSP mass	Hi-vol and 5-stage impactor 24 h samples	Gravimetric	Two sites in SW	5/80– 8/80 (123 days)
3	Barfoot et al. (1984)	TSP elemental composition	Hi-vol, 24 h samples	PIXE	SW	15/11/80–15/02/81 (51 days)
4	Bravo et al. (1989)	TSP; SO_4^{2-}, NO_3^-	Hi-vol, 24 h samples	Gravimetric, ion chromatography	Two sites in SW	1/81–3/88 (912 days)
5	Salazar et al. (1992)	PSD (0.49 to > 7.2 μm)	5-stage impactor	Gravimetric	SW	1986 (32 days)
6	Aldape et al. (1991a)	TSP elemental composition and BC	Hi-vol, 6 h samples	PIXE and LIMP	NW	One week in 04/88, 07/88, 11/88 and 01/89 (28 days)
7	Aldape et al. (1991b)	TSP elemental composition and BC	Hi-vol, 4 h samples	PIXE and LIMP	NW	Once per week, 3/88–2/90 (49 days)
8	Barbiaux et al. (1991), Vega et al. (1997)	TSP; PM2.5, SO_4^{2-}, NO_3^-; EC; OC	Hi-vol, single and dual filter packs 12 h samples	Gravimetric, PIXE, ion chromatography, and thermal optical	SW	12/89–2/90 (33 days)
9	Miranda et al. (1992)	PM(15–2.5) and PM2.5 analysis of elements heavier than neon, C, H	SFU 6 h samples	PIXE, LIMP and PESA	NW	22–28/08/90 (7 days)
10	Aldape et al. (1993)	TSP elemental composition.	Hi-vol, 6 h samples	PIXE	NW	18–25/04/88 (7 days)
11	Montañez and García-García, (1993)	PSD, CCN	Aerosol size analyzer, CCN counter		SW	22/07–9/08/85 (19 days)
12	Miranda et al. (1994)	PM(15–2.5) and PM2.5 analysis of elements heavier than neon, C, H	SFU 6 h samples	PIXE, LIMP and PESA	Two sites in NW	12–25/09/90 (14days) 12/02–1/03/91 (18 days)
13	Díaz-Francés et al. (1994) Nickerson et al. (1992)	PSD; CN	OPC; CN Counter		Aircraft	2/22/91 (14 days)
14	Rosas et al. (1995b)	PM10	Hi-vol 24 h samples	Atomic absorption	NW C SW	4 days per week Jan.–Dec. 1991 (208 days)

Table 3 (*continued*)

	Reference	Aerosol property measured	Instrumentation and sample rate	Analysis technique	Location	Measurement dates
15	Aldape et al. (1996a)	PM(15–2.5) and PM2.5, elemental composition	SFU 7–11 a.m. and 11 a.m. –3 p.m.	PIXE	NW	1 day per week Jan.–Dec. 1990 (52 days)
16	Miranda et al. (1996)	PM(15–2.5) and PM2.5, elemental composition	SFU 6 h samples	Gravimetric, PIXE, PESA and XRF	SW	16/10/93–10/12/93 (51 days)
17	Aldape et al. (1996b)	PM(15–2.5) and PM2.5, elemental composition	SFU 6 h samples	PIXE	C Two sites in SW	7 alternate days, between 25/11/93 and 5/12/93
18	Raga et al. (1999), Baumgardner et al. (2000)	PSD (0.05–0.7 μm); TC, OC, BC and SO_4^{2-}; Scattering and absorption coefficients	10-stage and six-stage impactors 24 h samples	DMA; EGA; Ion chromatography; nephelometer and soot photometer	SW	11/97 (14 days)
19	Flores et al. (1999)	PM(15–2.5) and PM2.5, elemental composition	SFU 12 h samples	PIXE	NE	26/07–23/08/96 (29 days) 14/02–14/03/97 (29 days)
20	Edgerton et al. (1999)	PM10 and PM2.5 elemental analysis for SO_4^{2-}, NO_3^-; Na, K, NH_4^+, OC and EC	Hi-vol 6 h samples at theree sites; 24 h samples at three sites	X-ray fluorescence, ion chromatography, atomic absorption, thermal/optical reflectance	Two sites in NE NW C SW SE	23/02–22/03/97 (29 days)
21	Miranda et al. (2000)	PM(15–2.5) and PM2.5 analysis of elements heavier than neon	SFU 6 h samples	PIXE	SW	14/08–15/09/95 (22 days)
(b) Biological particle measurement summary						
1	Rosas et al. (1987)	Airborne algae	Bubble flasks with Bold's basal medium One sample per day	Culture, isolation and identification	SW	7/82–8/82 7/85–12/85 (31 days)
2	Rosas et al. (1989)	Airborne algae	Bubble flasks with Bold's basal medium (1/day)	Culture, isolation and identification	SW	1/85–10/85 (46 days)
3	Rivera et al. (1992)	Isolated total protozoa	Impaction in impinger with Bold's basal medium Once per day (11:00–13:30)	Incubation and culture in several media. Identification and counting	NE, NW, SE SW	2/88–1/89 (260 days)
4	Rosas et al. (1992)	*Aspergillus* spores and	Two-stage Andersen, 3	Cultured by plates incubation.	SW	1/90–12/90

Table 3 (*continued*)

	Reference	Aerosol property measured	Instrumentation and sample rate	Analysis technique	Location	Measurement dates
		isolated fungal propagules	times per day; 5 days per week	Counting and identification		(250 days)
5	Rosas et al. (1993)	*Penicillium* spores	Two-stage Andersen, 22 mornings	Cultured by plates incubation. Counting and identification	NE, C, SW	2/90–10/90 (22 days)
6	Rivera et al. (1994)	*Amoebae*	Impaction in impinger with Bold's basal medium Once per day (11:00–13:30)	Incubation and culture in appropriate media Identification and counting	NE NW SE SW	2/88–1/89 (260 days)
7	Rosas et al. (1994)	Total airborne bacteria	Six-stage impactor 3 times per week at noon	Plates incubation, isolation, counting and identification	SW	1/89–12/89 (150 days)
8	Calderón et al. (1995)	Basidiomycete spores	Volumetric spore trap Burkard collected on tapes, 7-day samples	Tapes cut for 24 h exposure analysis and identification on microscope	C SW	1/91–12/91 (358 days)
9	Rosas et al. (1995a)	Proteins	Hi-vol, 24 h samples	Extraction from filters, MW and concentration determined	NE, C, SW	1/91–12/91 (50 days)
10	Calderón et al. (1997)	Deuteromycete spores	Volumetric spore trap Burkard 7-day samples	Tapes cut for 24 h exposure analysis and identification on microscope	C SW	1/91–12/91 (365 days)
11	Rosas et al. (1997)	*Escherichia coli*	Two-stage Andersen 2 samples per week	Incubation, isolation from gram-negative, identification and plasmid analysis	SW	4/96–05/1996 (16 days)
(c) Particle measurement summary radiative properties						
1	Galindo and Muhlia (1970)	Turbidity	Pyrheliometer		SW	1912, 1913, 1927, 1957
2	Galindo and Bravo (1975)	Turbidity	Pyrheliometer		SW	11/74–2/75
3	Muhlia et al. (1989)	Column integrated aerosols	Actinometer (hourly)		SW Two sites outside MC	5/84–3/85 (11 days)
4	Vasilyev et al. (1992, 1995a, 1995b)	Spectral optical depth	Spectrophotometer (1 h after sunrise, sampling for 2 h)		SW (24 days)	4/92–6/92
5	Galindo et al. (1995)	UV irradiance	Photometer (hourly)		SW (880 days)	3/90–8/92
6	Jáuregui and Luyando (1999)	Global radiation	Pyranometer (hourly)		C NE	1/94–12/98 (1825 days)

Table 4
Sampling days for aerosols

	Location	Condition	Elemental analysis	OC/EC analysis	SO_4/NO_3 analysis	Size distribution	Coarse mass	Fine mass	Optical properties	Bio-aerosols
Before 1992	NE	Wet								296
		Dry								296
	NW	Wet	54	55			28	47		260
		Dry	72	70			46	44		260
	C	Wet								397
		Dry								397
	SW	Wet		90	546	10	669	123		911
		Dry	51	123	579	22	630	33		880
	SE	Wet								260
		Dry								260
After 1992		Wet	29				29	29		
	NE	Dry	87	58	58		87	87		
	NW	Wet								
		Dry	146	72	72	14	146	146	14	
	C	Wet								
		Dry	65	58	58		65	65		
	SW	Wet								
		Dry	146	72	72	14	146	146	14	16
	SE	Wet								
		Dry	58	58	58		58	58		

0.4–0.59 μm are responsible for most of the light scattering.

- A high correlation is found between sulfate and nitrate concentrations and turbidity.
- Derived optical thickness is found between 0.6–1.2 and 0.5–0.8 in UV and visible wavelengths, respectively, and single scattering albedos of 0.7–0.9 and 0.6–0.8 for UV and visible wavelengths, respectively. Direct measurements of the scattering and absorption coefficients at visible wavelengths by Baumgardner et al. (2000) agree well with the derived estimates by Vasilyev et al. (1995a).
- Large diurnal variations in UV irradiance are observed and a significant impact on solar radiation is due to volcanic emissions. An increase in optical depth of 3% is estimated when volcanic aerosols are transported over the city.
- Annual temperatures near city edges are declining, attributed to the smog layer transported from the city.

5. Discussion

Tables 2 and 3 summarize the majority of observational studies that have been conducted over the past 40 years. The measurements are listed chronologically and are briefly described by the publications that discuss them, the species measured, the techniques used to make the measurement, and the locations and dates of the samples. A number of observations can be made, based on these tables and concerning the current state of our knowledge about gases and aerosols in Mexico City.

In the second section of this paper the diurnal, seasonal and year to year variations with respect to location were demonstrated with a sample of RAMA data. Aside from the gas and PM-10 measurements made at the RAMA sites there are no speciated HC measurements that can adequately characterize diurnal or geographical variations and the seasonal information is limited in its scope. The same is true for aerosols over virtually all space and temporal scales. An attempt has been made to obtain representative samples of some of the major gas species and the mass and elemental composition of aerosols from the five sectors of the city in both wet and dry seasons. There have been very few measurements made close to major sources of pollution, however, in order to measure the components of primary emission, e.g., more information is needed at locations directly next to major highways, concentration points of public transports, cottage industries using biomass burning (adobe brick, tile making, etc.) or other industries producing large quantities of combustion products. Secondly, the dispersion of pollutants and their interaction with the environment is clearly a three-dimensional problem; however, with the exception of a

limited set of balloon and aircraft measurements there is very little information on gases and particles in the vertical dimension.

Also discussed in the second section was the need to address the primary scientific issues that concern the processes that govern the formation and development of anthropogenic gases and aerosols, primarily those of photochemical production of secondary gases and aerosols. In general, the measurements of gases and aerosols have served to track trends in statistical quantities, i.e. minimum, maximum, and average, but there has been practically no analysis of the measurements with respect to physical processes behind these trends. There are some exceptions, such as the study of Raga and LeMoyne (1996), who analyzed O_3 and SO_2 data and put forward the hypothesis of an existing horizontal vortex (with anticlockwise rotation) within the basin. Such a vortex has been inferred from profiler data and has been modeled by regional meteorological models (Doran, Whiteman, and Banchett, pers. comm.). Also, with the exception of measurements of NO_2 photolysis rates (Castro et al., 1995), there is no information about photolysis rates of other photochemically important gases like O_3 or VOCs. Riveros (1996) ventured a guess that O_3 production is more sensitive to NO_x than to HCs. However, the measurement database is inadequate to make such speculations until much more is known about the chemical nature of both the primary and secondary HCs. A recent study (Molina, 2000) confirmed that the ratio VOC/NO_x ranges between 19 : 1 and 34 : 1 ppbC/ppb, and indicates that O_3 concentrations seem to be more sensitive to NO_x levels. The study also proposes that additional measurements of PAN, nitric acid and hydrogen peroxide are needed in order to better assess the photochemical situation in Mexico City.

There have been a number of measurements of HCs using GC, but these measurements have only identified a very limited number of species. There is a strong need for more spectral (infrared and mass fragmentation pattern) analysis of GC measurements, in particular the identification of less recognizable peaks in the GC chromatogram that represent compounds in small quantities yet of toxicological importance. A prime example of these are the pesticide compounds that have recently been identified in urban areas (Cortes and Hites, 2000) that are hazardous to health and can be transported on regional or synoptic scales.

Table 4 summarizes all the aerosol measurements that have been made in Mexico City and presents the number of days of samples taken and analyzed for different aerosol characteristics. It is evident that there are almost no measurements of either size distributions or optical properties and yet, as discussed in Section 2, the evolution of aerosols and their impact on other environmental properties cannot be understood without a knowledge of these properties. There are a fair number of measurements of aerosol SO_4^{2-}, NO_3^-, OC and EC composition, but these were all from the result of a single, 1 month measurement campaign in 1997 (Edgerton et al., 1999) during the dry season. Rain and high humidity have a significant affect on aerosol composition (Raga et al., 1999; Baumgardner et al., 2000); thus, more size differentiated measurements are needed of the inorganic, organic carbon and soot content of aerosols in both the wet and dry seasons.

There were a large number of measurements made prior to 1992, of TSP and, to a lesser extent, FSP; however, they were primarily made in the SW sector of the city. A similar situation occurs after 1992 where the majority of the mass measurements are biased towards locations in the SW. In addition, although a fair amount of elemental analysis has been made of aerosols, most has been done on aerosols collected on either PM10 or PM2.5 filters. In the case of PM10, coarse mode aerosols will dominate the aerosol mass and elements identified may not be particularly important for health or the environment. Analyses of PM2.5 aerosols are important for health considerations, but lack of size differentiation diminishes our ability to understand the relative importance of the physical processes that formed these aerosols, e.g., nucleation and growth by condensation and coagulation. Although theoretical studies suggest that a large fraction of environmentally important aerosols form from secondary photochemical reactions of VOCs, without a size-differentiated analysis of the inorganic and organic composition, the importance of these formation processes cannot be evaluated.

The measurement of mass has been the primary focus of almost every one of the published studies. It is the surface area of particles, however, that is the critical characteristic in many of the processes in which aerosols are involved, i.e. transport of respirable particles, heterogeneous chemistry, and optical properties. In addition, the hygroscopicity of Mexico City aerosols has never been measured; however, it is this property that governs the ability of a particle to grow as it is inhaled or to form cloud droplets.

The biogenic properties of aerosols are characteristics of particles that require a much more in-depth study, regarding physical processes of transport and biochemical interactions with gases and inorganic aerosols, as well as the environmental triggers for their emission and behavior.

As seen in Table 4, a great deal of sampling was done in all five sectors of the city, but most of it prior to 1992. There have been few measurements in the past 8 years, even as the population continues to grow along with land development and increased stress on sewage treatment facilities, two of the major contributors to the biogenic aerosol population. In spite of the recognized importance of biogenic aerosols on human

health, there is far too little information about their size and composition of biogenic aerosols, particularly those biological aspects closely linked to land use in the vicinity of human activity. Many biogenic materials use non-biogenic aerosols as their carrier, but this aspect of aerosol properties has not been explored enough in Mexico City.

6. Recommendations

In light of the large variations in gas and aerosol emissions and their subsequent evolution and interaction with their environment, dependent upon location, time of day and season, more frequent and widespread measurements are clearly needed. The quality of the measurements is as important as the quantity, specifically in obtaining a much broader range of organic gas and particulate species. Mobile ground stations can measure pollutants close to their source. The measurement platforms and techniques should utilize state-of-the-art advances, particularly for obtaining vertical profiles of gas and aerosol species. Aircraft provide an important means of obtaining these measurements but balloons and passive and active remote sensing hold promise for measuring time varying vertical structure of ozone, some hydrocarbons, water vapor and aerosols. Wind profilers are essentials for understanding complex circulation that contributes to the transport of urban pollutants.

Modeling studies of Mexico City meteorology and photochemistry that have been published in the open literature will be the subject of another review currently under way, that will complement the present paper. Very few models have been developed, however, to investigate gas, aerosol, and radiative processes in Mexico City. Models, coupled with observations, are valuable tools for evaluating these processes and more effort should be devoted to developing these models.

There have been limited laboratory studies that look at gas and particle formation and evolution under controlled conditions. A key to understanding such processes in their natural environment is an evaluation of the complex components that contribute to these processes. Well-designed laboratory studies play an important role in unraveling these processes.

There is a wealth of data that has been accumulated in the past 40 years in Mexico City, yet very little evaluation of this database has been undertaken to understand the physical processes that are most important in ozone production and aerosol formation and evolution. A part of the problem is the lack of trained personnel who can work on all aspects of air quality studies. Human resources are needed at all levels—student, technician, engineering and scientific, to design and conduct experiments and to evaluate and document the observations.

An understanding of the processes that underlie the degradation of air quality in Mexico City is essential before effective mitigation strategies can be implemented by government and health officials. Limited progress can be made, however, until a substantial investment in material and human resources is made to develop measurement programs and the associated infrastructure that systematically address the most critical aspects of the problem.

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Appendix A. Terminology

BC	black carbon
CCN	cloud condensation nuclei
CN	condensation nuclei
DMA	differential mobility analyzer
EC	elemental carbon
EGA	evolved gas analysis
FSP	fine suspended particles
GC	gas chromatography
GFC	gas filter correlation
Hi-Vol	high volume sampler
HPLC	high performance liquid chromatography
LIPM	laser integrating plate method
MCMA	Mexico City metropolitan area
MOUDI	micro-orifice uniform deposit impactor
MS	mass spectrometry
MW	molecular weight
PESA	proton elastic scattering analysis
PIXE	proton induced X-ray emission
PSD	particle size distribution
OC	organic carbon
RP	respirable particles
SFU	stacked filter unit
TC	total carbon
TSP	total suspended particles
VOC	volatile organic carbon
XRF	X-ray fluorescence

References

Aldape, F., Flores, F., Diaz, R.V., 1991a. Seasonal study of the composition of atmospheric aerosols in Mexico City. International Journal of PIXE 1 (4), 355–371.

Aldape, F., Flores, F., Diaz, R.V., 1991b. Two years of elemental composition of atmospheric aerosols in Mexico City. International Journal of PIXE 1 (4), 373–388.

Aldape, F., Flores, F., Diaz, R.V., 1993. Temporal variations in elemental concentrations of atmospheric aerosols in Mexico City. Nuclear Instruments and Methods in Physics Research B 75, 304–307.

Aldape, F., Flores, J., Garcia, R., Nelson, J.W., 1996a. PIXE analysis of atmospheric aerosols from a simultaneous three site sampling during the autumn of 1993 in Mexico City. Nuclear Instruments and Methods in Physics Research B 109/110, 502–505.

Aldape, F., Flores, J., Diaz, R.V., Crumpton, D., 1996b. PIXE and its applications to biological samples: present status. International Journal of PIXE 6 (1 and 2), 205–214.

Arriaga, J.L., Martínez, G., Escalona, S., Martínez, H., 1996. Compuestos orgánicos volatiles en la atmósfera de la ZMCM. In: García-Colin Scherer, L., Varela Ham, J.R. (Eds.), Contaminación Atmosférica. El Colegio Nacional, México, pp. 23–38.

Arriaga, J.L., Escalona, S., Cervantes, A.D., Orduñez, R., López, T., 1997a. Seguimiento de COV en aire urbano de la ZMCM 1992–1996. In: García-Colin Scherer, L., Varela Ham, J.R. (Eds.), Contaminación Atmosférica II. Universidad Autónoma Metropolitana, México, pp. 67–96.

Arriaga, J.L., Escalona, S., Cervantes, A.D., Orduñez, R., López, T., Trejo, G., Castillo, C., 1997b. Investigación sobre materia particulada y deterioro atmosférico. Tarea 1. medición de los compuestos orgánicos volátiles y semivolátiles en la atmósfera de la zona metropolitana de la Ciudad de México. Informe Técnico Final, GCA9746. Instituto Mexicano del Petróleo.

Báez, A.P., Reyes, M., Rosas, I., Mosiño, P., 1988. CO_2 concentration in the highly polluted atmosphere of Mexico City. Atmosfera 1, 87–98.

Báez, A.P., Belmont, R.D., González, O.G., Rosas, I.P., 1989. Formaldehyde levels in air and wet precipitation at Mexico City, Mexico. Environmental Pollution 62, 153–169.

Báez, A.P., Padilla, H., Belmont, R., 1995a. Scavenging of atmospheric formaldehyde by wet precipitation. Environmental Pollution 79, 271–275.

Báez, A.P., Belmont, R., Padilla, H., 1995b. Measurements of formaldehyde and acetaldehyde in the atmosphere of Mexico City. Environmental Pollution 89, 163–167.

Báez, A.P., Belmont, D.R., 1996. Niveles de carbonilos en la atmósfera de la ciudad de Mexico. In: García-Colin Scherer, L., Varela Ham, J.R. (Eds.), Contaminación Atmosférica. El Colegio Nacional, México, pp. 307–322.

Baumgardner, D., Raga, G.B., Kok, G., Ogren, J., Rosas, I., Baez, A., Novakov, T., 2000. On the evolution of aerosol properties at a mountain site above Mexico City. Journal of Geophysical Research 105, 22243–22253.

Barbiaux, M., Scheff, P.A., Babcock, L.R., 1991. Characterization of respirable particulate matter in Mexico City, Mexico. 84th Annual Meeting on Air and Waste Association, June 16–21, Vancouver, B.C.

Barfoot, K.M., Vargas-Aburto, C., MacArthur, J.D., Jaidar, A., Garcia-Santibanez, F., 1984. Multi-elemental measurements of air particulate pollution at a site in Mexico City. Atmospheric Environment 18, 467–471.

Beaton, S.P., Bishop, G.A., Stedman, D.H., 1992. Emissions characteristics of Mexico City vehicles. Journal of Air and Waste Management Association 42, 1424–1429.

Blake, D.R., Rowland, F.S., 1995. Urban leakage of liquefied petroleum gas and its impact on Mexico City air quality. Science 269, 953–956.

Bravo, H.A., 1960. Variation of different pollutants in the atmosphere of Mexico City. Journal of the Air Pollution Control Association 10 (6), 447–449.

Bravo, H.A., Torres, R., Saavedra, M., Aguilar, S., 1982. Correlation between T.S.P., F.S.P. and visibility in a high altitude city (Mexico City). The Science of the Total Environment 24, 177–182.

Bravo, H.A., Camacho, R., Saavedra, M.I., Sosa, R., Torres, R., 1989. Concentrations of nitrates and sulfates in total suspended and respirable particles as a result of air pollution control strategies in Mexico City. 82nd Annual Meeting on Air and Waste Management Association, 25–30 June, Anaheim, CA, 89-15.5.

Bravo, H.A., Sosa, R., Torres, J., 1990. Time variations of sulfur dioxide concentrations in the metropolitan area of Mexico City. Geofisica Internacional 29-3, 137–147.

Bravo, H.A., Torres, R.J., 2000. The usefulness the introduction of reformulated gasolines in developing countries. Mexico City, real case study. Atmospheric Environment 34, 499–506.

Bravo, J.L., Salazar, S., 1982. Concentración del aerosol mineral en la zona sur de la ciudad de México. Geofisica Internacional 21-2, 139–155.

Bravo, J.L., Salazar, S., 1984. Algunos resultados sobre la concentración de compuestos organicos solubles en benceno en el aerosol atmosferico. Geofisica Internacional 23-4, 467–473.

Cahill, T., Morales, R., Miranda, J., 1996. Comparative aerosol studies of Pacific Rim cities: Santiago, Chile (1987); Mexico City, Mexico (1987–1990) and Los Angeles, USA (1973 and 1987). Atmospheric Environment 30, 747–749.

Calderón, C., Lacey, J., Mccartney, H.A., Rosas, I., 1995. Seasonal and diurnal variation of airborne basidiomycete spore concentrations in Mexico City. Grana 34, 260–268.

Calderón, C., Lacey, J., McCartney, A., Rosas, I., 1997. Influence of urban climate upon distribution of airborne Deuteromycete spore concentrations in Mexico City. International Journal of Biometeorology 40, 71–80.

Castro, T., Ruiz-Suárez, L.G., Gay, C., Helguera, M., Ruiz-Suárez, J.C., 1995. Direct measurements of NO_2 photolysis rates for Mexico City. Atmósfera 8, 137–142.

Castro, T., Ruiz-Suárez, L.G., Ruiz-Suárez, J.C., Molina, M.J., Mortero, M., 1997. Sensitivity analysis of a UV radiation transfer model and experimental photolytic rates of NO_2 in the atmosphere of Mexico City. Atmospheric Environment 31, 609–620.

Cortes, D.R., Hites, R., 2000. Detection of statistically significant trends in atmospheric concentrations of semivolatile pollutants. Environmental Science and Technology 34, 2826–2829.

Díaz-Francés, E., Ruiz, M.E., Sosa, G., 1994. Spatial stratification and multivariate analyses of Mexico City air pollution

data. In: Báldasano et al. (Eds.), Air Pollution II, Vol. 2. Computational Mechanics Publications, Southampton.

Edgerton, S., Bian, X., Doran, J., Fast, J., Hubbe, J., Malone, E., Shaw, W., Whiteman, C., Zhong, S., Arriaga, J., Ortiz, E., Ruiz, M., Sosa, G., Vega, E., Limon, T., Guzman, F., Archuleta, J., Bossert, J., Elliot, S., Lee, J., McNair, L., Chow, J., Watson, J., Coulter, R., Doskey, P., Gaffney, J., Marley, N., Neff, W., Petty, R., 1999. Particulate air pollution in Mexico City: a collaborative research project. Journal of Air and Waste Management Association 49, 1221–1229.

Fernández, A.A., Ashore, M.R., 1995. Exposure of commuters to carbon monoxide in Mexico City. I: measurement of in-vehicle concentrations. Atmospheric Environment 29 (4), 525–532.

Flores, J., Aldape, F.R.V., Díaz, B., Hernandez-Mendez, B., Garcia, R., 1999. PIXE analysis of airbone particulate matter from Xalostoc, Mexico: winter to summer comparison. Nuclear Instruments and Methods in Physics Research 150, 445–449.

Gaffney, J.S., Marley, N.A., Cunningham, M.M., Doskey, P.V., 1999. Measurements of peroxyacyl nitrates (PANS) in Mexico City: implications for megacity air quality impacts on regional scales. Atmospheric Environment 33, 5003–5012.

Galindo, I., Muhlia, A., 1970. Contribution to the turbidity problem in Mexico City. Archives for Meteorology, Geophysics and Bioclimatology B 18, 169–185.

Galindo, I., Bravo, J.L., 1975. On the presence of a volcanic stratospheric dust stratum over a polluted atmosphere: Mexico City. Geofisica International 15, 157–167.

Galindo, I., Frank, S., Bravo, H., 1995. Ultraviolet irradiation over Mexico City. Journal of Air and Waste Management Association 45, 886–892.

Gamas, E.D., et al., 1999. Exhaust emissions from gasoline- and LPG-powered vehicles operating at the altitude of Mexico City. Journal of Air and Waste Management Association 49, 1179–1189.

Garcia, G.A., Herrera, M., Bravo, H., 1991. Ozone concentrations related to new blends in gasoline sold in Mexico City: a statistical analysis. Annual Meeting on Air and Waste Association 16–21 June, Vancouver, B.C.

González, R., Páramo, V., Sánchez, C., Pérez, G., Domínguez, R., 1993. Temporal-spatial analysis of carbon monoxide in Mexico City Metropolitan Area. The Science of the Total Environment 134, 93–101.

Jáuregui, E., Luyando, E., 1999. Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico City. International Journal of Climatology 19, 683–692.

Juárez, A., Gay, C., Bravo, J.L., 1995. Influence of urban ozone in the measurements of the total ozone column in Mexico City. Atmósfera 8, 35–43.

Kretzschmar, J.G., 1994. Particulate matter levels and trends in Mexico City, Sao Paulo, Buenos Aires and Rio de Janeiro. Atmospheric Environment 28, 3181–3191.

MARI, 1994. Mexico City Air Quality Research Initiative. A joint report of Los Alamos National Laboratory and the Mexican Petroleum Institute, LA-12699.

Miranda, J., Morales, J.R., Cahill, T., Aldape, F., Flores, J., 1992. A study of elemental contents in atmospheric aerosols in Mexico City. Atmosfera 5, 95–108.

Miranda, J., Cahill, T.A., Morales, R., Aldape, F., Flores, J., Diaz, R.V., 1994. Determination of elemental concentrations in atmospheric aerosols in Mexico City using proton induced X-ray emission, proton elastic scattering, and laser absorption. Atmospheric Environment 28, 2299–2306.

Miranda, J., Andrade, E., López-Suárez, A., Ledesma, R., Cahill, T.A., Wakabayashi, P.H., 1996. A receptor model for atmospheric aerosols from a southwestern site in Mexico City. Atmospheric Environment 30, 3471–3479.

Miranda, J., Crespo, I., Morales, M.A., 2000. Absolute principal component analysis of atmospheric aerosols in Mexico City. Environmental Science and Pollution Research 7, 1–5.

Molina, M., 2000. Proyecto para el diseño de una estrategia integral de gestión de la calidad del aire en el Valle de México 2001–2010; http://eaps.mit.edu/megacities/Reports.html.

Montañez, R.A., García-García, F., 1993. Some urban and meteorological effects on the production of cloud condensation nuclei in Mexico City. Atmosfera 6, 39–49.

Mugica, V., Vega, E., Arriaga, J.L., Ruíz, M.E., 1998. Determination of motor vehicle profiles for non-methane organic compounds in the Mexico City Metropolitan Area. Journal of Air and Waste Management Association 48, 1060–1068.

Muhlia, A., Leyva, A., Bravo, J.L., 1989. Actinometric method for the determination of the total number of aerosol particles in the vertical atmospheric column. Geofisica Internacional 28-1, 47–71.

Nava, M., Sanchez, G., Reyes, E., Barrera, A., 1996. Ozone ground levels as an air quality indicator for the Mexico City Metropolitan Area (MCMA) from 1986 to 1994. In: Caussade et al. (Eds.), Air Pollution IV. Computational Mechanics Publications, Southampton.

Nava, M., Sanchez, G., Reyes, E., 1997. Aplicación de técnicas de correlación a registros de ozono de la red Automática de Monitoreo Atmosférico. Contaminación Atmosférica II, El-Colegio Nacional, Mex.

Nickerson, E., Sosa, G., Hochstein, H., McCaslin, P., Luke, W., Schanot, A., 1992. Project Aguila: in situ measurements of Mexico City air pollution by research aircraft. Atmospheric Environment 26B, 445–451.

Nickerson, E., McCaslin, C.P., Sandoval, E., Paramo, V.H., Gonzalez, E., 1993. Aircraft observations of ozone, carbon monoxide and NO_x over Mexico City during project AGUILA. In: Zanneti, P., Brebia, C.P., Garcia Gardea, J.E., Ayala Milian, G. (Eds.), Air Pollution I. Computational Mechanics Publications, Southampton.

Perez Vidal, H., Raga, G.B., 1998. On the vertical distribution of pollutants in Mexico City. Atmosfera 11, 95–108.

PROAIRE, 1996. Programa para mejorar la calidad del aire en el valle de Mexico, 261pp.

Raga, G.B, LeMoyne, L., 1996. On the nature of air pollution dynamics in Mexico City. Part I: non-linear analysis. Atmospheric Environment 30, 3987–3993.

Raga, G.B, Kok, G.L., Baumgardner, D., Báez, A., Rosas, I., 1999. Evidence for volcanic influence on Mexico City aerosols. Geophysical Research Letters 26, 1149–1152.

Rivera, F., Lugo, A., Ramírez, E., Bonilla, P., Calderón, A., Rodríguez, S., Ortiz, R., Gallegos, E., Labastida, A., Chávez, B., 1992. Seasonal distribution of air-borne protozoa in

Mexico City and its suburbs. Water, Air and Soil Pollution 61, 17–36.

Rivera, F., Lugo, A., Ramírez, E., Bonilla, P., Calderón, A., Rodríguez, S., Ortiz, R., Gallegos, E., Labastida, A., Chávez, M., 1994. Seasonal distribution of air-borne pathogenic and free-living amoebae in Mexico city and its suburbs. Water, Air and Soil Pollution 74, 65–87.

Riveros, H.G., Alba, A., Ovalle, P., Silva, B., Sandoval, E., 1998a. Carbon monoxide trend, meteorology and three-way catalysts in Mexico City. Journal of Air and Waste Management Association 48, 459–462.

Riveros, H.G., Arriaga, J.L., Tejeda, J., Julián-Sánchez, A., Riveros-Rosas, H., 1998b. Ozone and its precursors in the atmosphere of Mexico City. Journal of Air and Waste Management Association 48, 866–871.

Riveros, H.G., 1996. Análisis de las mediciones de contaminación del aire. Contaminacion Atmosférica I. El Colegio Nacional, Mex.

Rosas, I., Roy-Ocotla, G., Mosiño, P., Baez, A., Rivera, I., 1987. Abundance and heterogeneity of algae in the Mexico City Atmosphere. Geofisica Internacional 26 (3), 359–373.

Rosas, I., Roy-Ocotla, I.G., Mosiño, P., 1989. Meteorological effects on variation of airborne algae in Mexico. International Journal of Biometeorology 33, 173–179.

Rosas, I., Calderón, C., Escamilla, B., Ulloa, M., 1992. Seasonal distribution of Aspergillus in the air of an urban area: Mexico City. Grana 31, 315–319.

Rosas, I., Calderon, C., Ulloa, M., Lacey, J., 1993. Abundance of airborne Penicillium CFU in relation to urbanization in Mexico City. Applied and Environmental Microbiology 59, 2648–2652.

Rosas, I., Yela, A., Santos-Burgoa, C., 1994. Occurrence of airborne enteric bacteria in Mexico City. Aerobiologia 10, 39–45.

Rosas, I., Yela, A., Salinas, R., Arreguin, E., Rodríguez-Romero, A., 1995a. Preliminary assessment of protein associated with airborne particles in Mexico City. Aerobiologia 11, 81–86.

Rosas, I., Belmont, R., Jauregui, E., 1995b. Seasonal variation of atmospheric lead levels in three site in Mexico City. Atmosfera 8, 157–168.

Rosas, I., Salinas, E., Yela, A., Calva, E., Eslava, C., Cravioto, A., 1997. Escherichia coli in settled-dust and air samples collected in residential environments in Mexico City. Applied and Environmental Microbiology 63, 4093–4095.

Ruiz-Suárez, L.G., Imaz, M., Mar, M.B., 1993. Calculations of natural hydrocarbon emissions in the Valley of Mexico. In: Zanneti, P., Brebia, C.A., Garcia Gardea, J.E., Ayala Milian, G. (Eds.), Air Pollution I. Computational Mechanics Publications, Southampton.

Ruiz-Suárez, L.G., Andraca-Ayala, G.L., 1997. Gas phase determination of aldehydes in three sites of México City. In: Power, H., Tirabassi, T., Brebbia, C.A. (Eds.), Air Pollution V. Modelling, Monitoring and Management. Computational Mechanics Publications, Southampton.

Salazar, S., Bravo, J.L., Falcón, Y., 1981. Sobre la presencia de algunos metales pesados en la atmósfera de la ciudad de México. Geofisica Internacional 20-1, 41–54.

Salazar, S., Bravo, J.L., 1986. Sulfatos y nitratos en particulas atmosféricas y su relación con algunos parametros ópticos. Geofisica Internacional 25-3, 455–469.

Salazar, S., Bravo, J.L., Castellanos, M.A., 1989. Identificación de la fracción mineral del aerosol atmosférico, en una zona urbana de la ciudad de México por medio de diffración y fluorescencia de rayos-X. Atmósfera 2, 103–110.

Salazar, S., Lemoyne, L., Rosas, I., 1992. Preliminary results of size distribution airborne particles in Mexico City. Water, Air and Soil Pollution 64, 649–658.

Seinfeld, J.H., Pandis, S.N., 1998. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. John Wiley and Sons, New York.

Seila, R.L., Lonneman, W.A., 1993. VOC's in Mexico City Ambient Air. EPA Technical Report No. EPA/600/A-93/169, 7 pages.

Streit, G.E., Guzmán, F., 1996. Mexico City: progress of an international collaborative project to define air quality management options. Atmospheric Environment 5, 723–733.

Tejeda, J., Aquino, V., 1993. On the remote sensing of automotive CO and HC emissions in Mexico City. In: Zanneti, P., Brebia, C.A., Garcia Gardea, J.E., Ayala Milian, G. (Eds.), Air Pollution I. Computational Mechanics Publications, Southampton.

Vasilyev, O., Ivlev, L., Muhlia, A., Leyva, A., Peralta-Fabi, R., 1992. Influence of aerosol on radiative transfer in the polluted atmosphere. Proceedings of the International Radiation Symposium. Tallin, Estonia, 3–8 August, pp. 195–198.

Vasilyev, O., Leyva Contreras, A., Muhlia Velazquez, A., Peralta Fab, R., Ivlev, I.S., Kovalenko, A.P., Vasiyev, A.V., Jukov, V.M., Welch, R., 1995a. Spectral optical properties of the polluted atmosphere of Mexico (Spring–Summer 1992). Journal of Geophysical Research 100, 26027–26044.

Vasilyev, O., Welch, R.M., Muhlia, A., Leyva, A., Peralta-Fabi, R., 1995b. Passive optical remote sensing of aerosol air pollution in urban and rural regions. Proceedings of the 10th World Clean Air Congress, Espoo, Finland, 28 May–2 June, pp. 330–333.

Vega, E., Garcia, I., Apam, D., Ruíz, M.E., Barbiaux, M., 1997. Application of a chemical mass balance receptor model to respirable particulate matter in Mexico City. Journal of Air and Waste Management Association 47, 524–529.

WHO/UNEP, 1992. Urban Air Pollution in Megacities of the World. World Health Organization, United Nations Environment Programme, Blackwell, Oxford.