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Megacities and Atmospheric Pollution

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ABSTRACT

About half of the world's population now lives in urban areas because of the opportunity for a better quality of life. Many of these urban centers are expanding rapidly, leading to the growth of megacities, which are defined as metropolitan areas with populations exceeding 10 million inhabitants. These concentrations of people and activity are exerting increasing stress on the natural environment, with impacts at urban, regional and global levels. In recent decades, air pollution has become one of the most important problems of megacities. Initially, the main air pollutants of concern were sulfur compounds, which were generated mostly by burning coal. Today, photochemical smog—induced primarily from traffic, but also from industrial activities, power generation, and solvents—has become the main source of concern for air quality, while sulfur is still a major problem in many cities of the developing world. Air pollution has serious impacts on public health, causes urban and regional haze, and has the potential to contribute significantly to climate change. Yet, with appropriate planning, megacities can efficiently address their air quality problems through measures such as application of new emission control technologies and development of mass transit systems.

This review is focused on nine urban centers, chosen as case studies to assess air quality from distinct perspectives: from cities in the industrialized nations to cities in the developing world. While each city—its problems, resources, and outlook—is unique, the need for a holistic approach to the complex environmental problems is the same. There is no single strategy in reducing air pollution in megacities; a mix of policy measures will be needed to improve air quality. Experience shows that strong political will coupled with public dialog is essential to effectively implement the regulations required to address air quality problems.

INTRODUCTION

Nearly half of the world's population (48%) in 2000 lived in urban areas, and the number of urban dwellers is expected to grow by 2% per year during the coming three decades.[1] Table 1 shows that world population is expected to increase from 6.1 billion in 2000 to 8.1 billion in 2030, with nearly all of this growth concentrated in urban areas (from 2.9 billion to 4.9 billion). Urban populations in less developed regions will double from 2 billion to 3.9 billion. These concentrations of people and their activities have consequences at urban, regional, continental, and global scales.[2] However, as centers of economic growth, education, technological advancement, and culture, large cities also offer opportunities to manage the growing population in a sustainable way.

The growth of urban environments presents a major challenge. This review addresses the effects of large urban areas on the Earth's atmosphere, in the cities themselves and beyond their borders. The topic is broad, and hence only a selection of the relevant issues is considered. Urban planning, industrial development, transportation, and other topics are discussed in the context of their interactions with air quality.

A megacity is often defined as a metropolitan area with more than 10 million inhabitants. This definition is arbitrary, as major urban centers often include people who are not located within a city's political boundaries. Nine urban centers are examined in this review as case studies: 1) Los Angeles, CA; 2) Mexico City, Mexico; 3) Toronto, Canada; 4) Delhi, India; 5) Beijing, China; 6) Santiago, Chile; 7) São Paulo, Brazil; 8) Bogotá, Colombia; and 9) Cairo, Egypt. These cities range from urban areas with relatively clean air in industrialized nations to highly polluted cities in the developing world. In particular, these cities have been active in assessing and reporting on air quality and are aggressively undertaking efforts to improve it.

In this review, the driving forces behind the formation and growth of megacities are described. The nature of megacities, their air quality problems, and the associated science are briefly addressed. The situations in the case-study

Table 1. Distribution of global population by size of settlement (1950–2030).

	Population (in billions)				
Major Area	**1950**	**1975**	**2000**	**2003**	**2030**
World	2.52	4.07	6.07	6.3	8.13
More developed regions	0.81	1.05	1.19	1.2	1.24
Less developed regions	1.71	3.02	4.88	5.1	6.89
Urban population					
World	0.73	1.52	2.86	3.04	4.94
More developed regions	0.43	0.7	0.88	0.9	1.01
Less developed regions	0.31	0.81	1.97	2.15	3.93
Rural population					
World	1.79	2.55	3.21	3.26	3.19
More developed regions	0.39	0.34	0.31	0.31	0.23
Less developed regions	1.4	2.21	2.9	2.95	2.96

Source: United Nations Population Division, World Urbanization Prospects, The 2003 Revision.[1]

megacities are discussed, as are their air quality management programs. Air quality management tools available for large urban centers are summarized and an outlook of the air quality situation in coming years is given. A more detailed description of air quality management strategies applied in the nine case study cities is available as an online supplement to this review.[3]

CAUSES AND CONSEQUENCES OF URBAN GROWTH

The number and size of megacities increased dramatically during the second half of the twentieth century. In 1800, London was the only major city in the world, with a population of 1 million. Cities with a population of at least 1 million increased to three by the beginning of the twentieth century; today, there are 281. The average population of the 100 largest cities was 200,000 in 1800; this increased to 2.1 million by 1950, 5 million by 1990, and 7.7 million by 2002.[4] In 1900, 9 of the 10 largest cities were in North America and Europe, whereas today only 3 (Los Angeles, New York, and Tokyo) are in the developed world. In 1950, New York and Tokyo were the only megacities. That number grew to 4 (Tokyo, New York, Shanghai, and Mexico City) by 1975 and to 20 by 2000, and is estimated to reach 22 by 2015.[1]

Most of the world's urban population still lives in cities of fewer than 10 million inhabitants; many of these cities are growing faster than the megacities.[1] A metropolitan area (large population center that consists of several towns or cities clustered together) usually combines a conurbation proper (the contiguous built-up area) with peripheral zones not themselves necessarily urban in character but closely bound to the conurbation by employment or commerce. For example, the Mexico City metropolitan area (MCMA), often simply called Mexico City, consists of 16 delegations of the Federal District and 37 contiguous municipalities from the State of Mexico and one municipality from the State of Hidalgo, some with populations over 1 million, that make up the total population of ~20 million for this megacity.

Currently, there are 100 metropolitan areas with official populations exceeding 3 million. Whether several metropolitan areas are located in succession, they are sometimes grouped together as a megalopolis. A megalopolis consists of several large cities and their surrounding areas in sufficient proximity to be considered a single urban complex. The French geographer Jean Gottmann[5] coined the term "megalopolis" to describe the northeastern United States, a vast metropolitan area ("BosWash") more than 480 km long, stretching from Boston in the north to Washington, DC, in the south.[6]

Megacity is a general term for cities together with their suburbs or recognized metropolitan area usually with a total population in excess of 10 million people. There is no exact definition of its boundaries, where it starts and where it ends. As a result, the term "megacity" is used loosely in this review, referring to large agglomerations of people with their consequent employment, housing, transportation, and security needs.

Levels of urbanization correlate with national income, and within a country, wealth is concentrated in urban areas. Developed countries are more urbanized, and urban areas may produce ~60% of a country's gross national product.[7] This higher income is a major cause of growth, as people from the countryside move to the city for the jobs, education, and services that an urbanized center provides. Conflict, land degradation, and the depletion of natural resources also motivate migration, especially in Africa,[8] and international migration is another factor. But the largest contributor to growth in urban settings is the increasing number of people in the world, especially in the developing world.

One of the main hypotheses in environmental economics suggests that as the per capita income of a nation increases, the environmental quality deteriorates up to a point. After that point, environmental quality improves as incomes continue to rise. The relationship has an "inverted U" shape and is known as the Kuznet's Curve.[9] The environmental deterioration related to increasing income at low-income levels is probably associated with increased industrialization. The association between improvement in environmental quality and higher income is less obvious. Wealthier nations can more easily prioritize environmental quality, implement more stringent control measures to reduce pollution, develop new technologies, and enforce environmental regulations more strictly. However, they may also export pollution, for example, by establishing factories or powerplants in other nations, by exporting used vehicles that are more polluting, or by simply purchasing goods that are produced in lower income, more environmentally compromised countries.[10]

Transportation is a major source of air pollution in many cities, especially in developing countries. The growing problems of congestion, accidents, and lack of security are also worrisome. Yet transportation is also a critical enabler of economic activity and beneficial social interactions. The challenge facing megacities is how to reduce the adverse environmental impacts and other negative effects of transportation without giving up the benefits of mobility. This dilemma becomes most pressing under conditions of rapid urban growth, which is likely to increase travel demand significantly.[11]

Growth in large cities is often accompanied by increases in urban poverty. The urban poor, who are often unskilled and unable to compete for scarce resources or protect themselves from harmful environmental conditions, are most affected by urbanization, especially in developing nations.[8] Land development processes tend to serve middle and higher income classes, forcing the poor to settle in high densities on marginal lands within cities or on the urban periphery. These urban area expansions often start as illegal settlements, sometimes in areas at risk from environmental hazards (such as floods and landslides), and without access to basic services (such as water and sanitation). More than half the population of Mexico City lives in such settlements.[11] As the peripheries of cities enlarge, agricultural land, forests, and wetlands are consumed. Sand and gravel are excavated and removed for increased construction; woodlands are depleted for fuel; and rivers, lakes, streams, and coastal waters are polluted by untreated sewage and runoff.

Urbanization and industrialization have important consequences for the Earth's atmosphere.[12] Biomass and coal used for heating and cooking pollute indoor and outdoor air. Disturbed land, unpaved roads, and construction add to atmospheric dust levels. Transport is often accomplished with old city buses and poorly maintained two-stroke engines operating with adulterated fuels that are not conducive to passing "smog tests." Undesirable properties near polluting industries are often settled first by the economically disadvantaged, further adding to their atmospheric pollution exposure. The regional and global dispersion of pollutants generated locally causes acid deposition, and changes in the Earth's radiation balance. Concerns about tropospheric ozone (O_3) and particulate matter (PM) have heightened recently because the long-range transport of these pollutants influences air quality and its effects on climate are felt in regions far from their sources.

Cities create heat islands that can also aggravate pollution. Between 1990 and 2000, the average annual temperature in Mexico City increased from 14.8 °C to 16.8 °C.[13] Higher ambient temperatures enhance O_3 and some secondary PM formation. Warmer temperatures in the summer increase the demand for cooling and electric energy consumption, leading to yet higher temperatures in the city.

Deterioration in urban environmental conditions can have serious effects on human health and welfare, particularly for the poor.[14] Air and water pollution cause chronic and infectious respiratory and water-borne diseases, and result in increased mortality rates.[15–19] However, worldwide epidemiological and demographic information suggests that survival rates are better in cities than in rural areas because of better access to health services.[7] Although local environmental problems diminish as cities become wealthier, environmental problems arise on larger scales. Wealthier urban residents rely heavily on fossil fuels and electricity that create more gaseous, liquid, and solid wastes.[20]

A city's ecological footprint (EF)[21] is the biological productive area required to produce the resources used, and to assimilate the wastes generated, by a defined population at a specified standard of living.[8] EF is a measure of the biological capacity of the Earth to create new resources and absorb waste. The Earth has ~11.4 billion hectares of productive land and sea space; about one-fourth of the Earth's surface area is unproductive. Divided among the Earth's 6 billion people in 2000, this equates to an average of 1.9 hectares per person. In 1999, the EF was less than 1.4 hectares per capita for the average African and Asian, 5 hectares for the average western European, and 9.6 hectares for the average North American. The global average EF during 1999 was 2.3 hectares per person, 20% more than the 2000 estimate, and a substantial increase from the 1961 EF of ~1.3 hectares per person. The EF is likely to grow to 180%–220% of the Earth's capacity by 2050,[22] clearly an unsustainable situation.

The world's richest countries, with 20% of the global population, account for 86% of total private consumption, whereas the poorest 20% of the world's population accounts for just 1.3% of consumption. A child born today in an industrialized country will add more to consumption and pollution over his or her lifetime than 30–50 children born in developing countries. The EF of wealthier consumers is a major cause for the exceedance of the Earth's carrying capacity.[23] A typical North American city with a population of 650,000 people would require 30,000 km^2, an area roughly the size of Vancouver Island in Canada, to meet its domestic needs—without including the environmental demands of industry. In contrast, a city of the same size in India would require only 2900 km^2.[8] However, when properly managed, EFs from urban areas can be smaller than those of a similar number of people in nonurban settings.

Cities can concentrate populations in a way that reduces land pressure and provides proximity to infrastructure and services.[7,24] Well-planned, densely populated settlements can reduce the need for land conversion and provide opportunities for energy savings. Sustainable development must include 1) appropriate air quality management plans that include the establishment of adequate monitoring capabilities for the surveillance of the environmental quality and health status of the populations; 2) adequate access to clean technologies, including the provision of training and development of extensive international information networks; and 3) improvement of data collection and assessment so that national and international decisions can be based on sound information.[25,26]

Urban air pollution is not a new problem, and effective emission reduction strategies are available for most emission sources. The formulation and implementation of effective integrated air quality management strategies will be crucial to address this challenge and to protect human health and welfare, as well as ecosystems.

AIR POLLUTION IN MEGACITIES

Megacities often contain high concentrations of PM; O_3; sulfur dioxide (SO_2); nitric oxide (NO) and nitrogen dioxide (NO_2), the sum of which is known as nitrogen oxides (NO_x); carbon monoxide (CO); volatile organic compounds (VOCs), and hydrocarbons (HC, a VOC subset).[27a] PM is often reported as mass concentration in the total suspended particulates (TSP), PM_{10}, and $PM_{2.5}$ (particles with aerodynamic diameters of less than ~40, 10, and 2.5 μm, respectively). The major PM chemical components are sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), organic carbon (OC), elemental carbon, and soil (a weighted sum of mineral elements such as aluminum [Al], silicon [Si], calcium [Ca], titanium [Ti], and iron [Fe]). Long-lived greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons are important on global scales.[27,28]

As shown in Table 2, the highest TSP and SO_2 levels appear mostly in Asian cities. These data are limited to cities that measure and report pollutant concentrations. A high priority action item should be to establish comprehensive monitoring in other cities in the developing world. More extensive atmospheric measurements and

Table 2. Megacities of the world and air pollution.

City	Population^a (millions)			TSP (μg/m^3) 1999^b	TSP (μg/m^3) 1995^c	SO_2 (μg/m^3) 1998^b	NO_x (μg/m^3) 1998^b
	1975	2000	2003				
Tokyo, Japan	26.6	34.4	35	43	49	18	68
Mexico City, Mexico	10.7	18.1	18.7	69	279	74	130
New York, USA	15.9	17.8	18.3	23		26	79
São Paulo, Brazil	9.6	17.1	17.9	46	86	43	83
Mumbai, India	7.3	16.1	17.4	79	240	33	39
Delhi, India	4.4	12.4	14.1	187	415	24	41
Kolkata, India	7.9	13.1	13.8	153	375	49	34
Buenos Aires, Brazil	9.1	12.6	13				
Shanghai, China	11.4	12.9	12.8	87	246	53	73
Jakarta, Indonesia	4.8	11	12.3	103	271	—	—
Los Angeles, USA	8.9	11.8	12	38		9	74
Dhaka, Bangladesh	2.2	10.2	11.6				
Osaka-Kobe, Japan	9.8	11.2	11.2	39	43	19	63
Rio de Janeiro, Brazil	7.6	10.8	11.2	40	139	129	—
Karachi, Pakistan	4	10	11.1				
Beijing, China	8.5	10.8	10.8	106	377	90	122
Cairo, Egypt	6.4	10.4	10.8	178		69	—
Moscow, Russian Federation	7.6	10.1	10.5				
Metro Manila, Philippines	5	10	10.4	60	200	33	—
Lagos, Nigeria	1.9	8.7	10.1				
WHO Standards				90	90	50	40

[a]United Nations Population Division, World Urbanization Prospects, The 2003 Revision.[1] City population is the number of residents of the city as defined by national authorities and reported to the United Nations. Mostly, the city refers to urban agglomerations. [b]World Development Indicators (2003).[29] Published by the World Bank, pp. 168–169. http://www.worldbank.org/data/wdi2003/pdfs/table%203-13.pdf. TSP data are for the most recent year available, most are for 1999; SO_2 and NO_x data are for the most recent year available in 1990–98. Most are for 1995. [c]World Development Indicators (2002).[30] http://www.worldbank.org/data/wdi2002/pdfs/table%203-13.pdf.

modeling are needed to define optimal emission control strategies. Policy-makers should use this information to balance the economic and social benefits of health improvements against the costs of emission control. In practice, because of large uncertainties in air pollution and health effects science, measurements and air quality models are best used to help prioritize controls on different primary emitters to achieve various air quality improvement goals.

Some pollution control decisions are easy. Exposure to SO_2 and SO_4^{2-} from burning coal was identified during London's "killer smog" events in the 1940s and 1950s, which were correlated with increased sickness and death. Switching to low-sulfur fuels improved this situation. Nevertheless, areas with high sulfur levels remain in some regions of the developing world. Determining the causes of high PM and O_3 concentrations is not as straightforward. NO_x and VOCs, much of which are emitted by the transportation sector, are transformed in the presence of sunlight to produce O_3, nitric acid (HNO_3), and other oxidants in a complex series of chemical reactions. These reactions also generate secondary PM organic compounds, NO_3^- and SO_4^{2-}. The relationship between NO_x, VOCs, and O_3 is nonlinear: fresh emissions of NO destroy O_3. High levels of NO_2 scavenge hydroxyl (OH) radicals, the reactive spp. that initiate the breakdown of VOCs. Reductions of NO_x or VOC emissions may have little or no effect on, or may even increase, O_3 concentrations.

The application and validation of air quality models requires spatially and temporarily resolved emissions data as well as knowledge of the meteorology (including solar radiation). In addition to commonly measured O_3, NO, NO_2, CO, and PM mass, individual VOCs and PM chemical compositions are needed. This detailed information is rarely available, however. Special studies are needed in megacities to better understand the causes of such emissions and to measure progress in limiting them. The following measurements from special studies in Mexico City demonstrate useful techniques that could be applied in other megacities:

- Routine hourly measurements of PM_{10}, O_3, NO, NO_2, and CO acquired from the Mexican Automatic Air Quality Monitoring Network (*Red Automática de Monitoreo Atmosférico*) provide a long-term record to determine the temporal and spatial characteristics of air pollution.
- Remote sensing of emissions from individual vehicles, obtained from absorption spectra of IR and UV light projected through the exhaust plume, quantifies NO, CO, CO_2, and HC. These tests indicated that 4% of the automobiles contributed 30% of the tailpipe HC emissions, and 25% of the vehicles contributed 50% of the CO emissions in 1991.[31] Most vehicles emitted 3–6% CO, suggesting that they were deliberately tuned for power without regard for emission reductions. Similar measurements in 1994 showed ~50% decrease in average CO and HC emissions, demonstrating the effectiveness of catalytic converters required on cars sold after 1991.[32] Remotely-sensed emissions in 2000[33] found higher emissions in lower income areas of the city. Nevertheless, average vehicle emissions decreased by 70% for CO and 90% for HC relative to 1991 values. For all these spp., the median emission is notably less than the average, which occurs because a fraction of vehicles have high emissions and thus disproportionately impact the average emissions. Past data shows that emissions of CO and HC decrease sharply after 1988, and NO_x emissions decrease sharply for cars manufactured after 1992.
- PAHs originate from emissions of motor vehicles, oil refineries, forest fires, and cooking. PAH concentrations along Mexico City roadways range from 60 to 910 ng/m^3.[34] These levels are approximately five times higher than concentrations measured in the United States and are among the highest measured ambient values reported. The large concentrations are likely due to a combination of old diesel-powered vehicles and the city's relatively dirty light-duty vehicle fleet, half of which lacked catalytic converters in 2003.
- In the spring of 2003, an MIT-led multinational team of experts conducted an intensive, five-week field campaign in the MCMA. The overall goal is to contribute to the understanding of the air quality problem in megacities by conducting measurements and modeling studies of atmospheric pollutants in the MCMA and to provide a scientific base for devising emissions control strategies.

EFFECTS OF EXCESSIVE POLLUTION IN MEGACITIES

Emissions and ambient concentrations of pollutants in megacities can have widespread effects on the health of their populations, urban and regional haze, and ecosystem degradation. Impacts on health, visibility, regional ecosystem (including acid and fixed nitrogen deposition, photochemical oxidant damage, and photosynthetically active radiation), regional climate change, and global pollutant transport are evaluated.

Adverse Health Impacts

Table 3 lists recommended air quality values set by various countries and the World Health Organization (WHO)

Table 3. Ambient air quality standards for the nine case study cities (countries).

	CO			SO_2			O_3			NO_2			PM_{10}		$PM_{2.5}$		Lead	
	ppm	µg/m³ × 10³	Time	ppm	µg/m³	Time	ppm	µg/m³	Time	ppm	µg/m³	Time	µg/m³	Time	µg/m³	Time	µg/m³	Time
WHO	26	30	1 h	0.13	350	1 h	0.08	160	1 h	0.21	400	1 h					0.5–1	1 yr
	9	10	8 h	0.05	125	24 h	0.06	120	8 h	0.08	150	24 h						
US National	35	40	1 h	0.14	365	24 h	0.12	235	1 h	0.05	100	1 yr	150	24 h	65	24 h	1.5	qtr
	9	10	8 h	0.03	80	1 yr	0.08	160	8 h				50	1 yr	15	1 yr		
Los Angeles	20	23	1 h	0.25	655	1 h	0.09	180	1 h	0.25	470	1 h	50	24 h	12	1 yr	1.5	30 d
	9	10	8 h	0.04	105	24 h							20	1 yr				
Mexico	11	13	8 h	0.13	350	24 h	0.11	216	1 h	0.21	400	1 h	150	24 h			1.5	qtr
				0.03	80	1 yr							50	1 yr				
India[a]				0.011	30	24 h				0.016	30	24 h	75	24 h			0.5	1 yr
				0.006	15	1 yr				0.008	15	1 yr	50	1 yr				
Colombia	35	40	1 h	0.13	350	24 h	0.08	160	1 h	0.17	320	1 h	160	24 h				
	10.5	12	8 h	0.03	80	1 yr	0.06	120	8 h	0.12	220	24 h	60	1 yr				
Brazil	35	40	1 h	0.14	365	24 h	0.08	160	1 h	0.17	320	24 h	150	24 h				
	9	10	8 h	0.03	80	1 yr				0.05	100	1 yr	50	1 yr				
Chile				0.14	365	24 h	0.08	160	1 h	0.05	100	1 yr	150	24 h				
				0.03	80	1 yr												
Canada	30	34	1 h	0.06	160	24 h	0.05	100	1 h	0.03	60	1 yr	30	24 h	50	24 h		
				0.011	30	1 yr												
China[a]	3.5	4	24 h	0.019	50	24 h	0.06	120	1 h	0.04	80	24 h	50	24 h			1.5	qtr
				0.008	20	1 yr				0.02	40	1 yr	40	1 yr				

Note: The conversion from the ppm to µg/m³ is considering 25C and 1 atm; [a]Sensitive areas.

to protect human health and welfare. The health effects of air pollution vary not only by the intensity and the duration of exposure, but also by the age and health status of the individual exposed. Populations at greater risk include children, the elderly, and those already suffering from diabetes or cardiovascular and respiratory disease.

Cohort studies follow individuals for many years to evaluate whether long-term exposure to air pollutants is related to mortality, taking into account other variables such as age, gender, occupation, weather, smoking status, etc. Time-series studies track daily changes in air pollution levels and correlate them with the number of deaths in the exposed population that occur during the same or possibly within the next few days. Only a few cohort mortality studies have been carried out.[35–38] In contrast, many time-series mortality studies have been conducted around the world, mainly because they can be conducted more quickly and at lower cost. In general, both sets of studies conclude that premature mortality associated with air pollution is caused predominantly by PM rather than by O_3, which is linked to morbidity. However, studies in Asia often find a stronger association between mortality and SO_2, rather than PM. Relatively high levels of SO_2 are one reason; another is that TSP data is more readily available than data for PM_{10}. Other reasons could be differences in age structure, health status, etc.

Mexico City health studies[39–43] indicate a 1% change in daily mortality per 10 µg/m³ increase in PM_{10} levels (the so-called risk coefficient). This compares with a 0.6% per 10 µg/m³ increase derived from a meta-analysis of epidemiological studies conducted around the world.[44] A major question in the MCMA time-series studies is whether the $PM_{2.5}$, PM_{coarse} ($PM_{10} - PM_{2.5}$), or both are causing the premature mortality effect. Another important question is whether the deaths involve infants and healthy young people, in addition to elderly individuals with pre-existing cardiopulmonary disease. Evans et al.[45] developed a simplified risk-benefit assessment for Mexico City by estimating the impact of a 10% reduction in air pollution exposures from baseline values prevailing in the late 1990s. They found that such a reduction could yield health benefits worth ~$2 billion per year. The economic benefits of air pollution control are potentially quite large but highly uncertain. The health benefits of reducing ambient O_3 levels appear to be only about one-tenth of those obtained through similar fractional reductions in PM_{10}, and the benefits of reductions in air toxics are even smaller.

The Ontario Medical Association in Canada estimated that 1900 premature deaths, 9800 hospital admissions, 13,000 emergency room visits, and 46 million illnesses were caused by air pollution in the province during the year CY 2000[46] (the population of Ontario is ~12 million people). Approximately 5000 preventable premature deaths (~8% of the total) in 11 Canadian cities were attributable to the combined effects of O_3, SO_2, NO_2, and

CO.[47] Other studies in 1995 estimated that pollution caused 1000 premature deaths and 5500 hospital admissions in the Greater Toronto area,[48] and 298 premature deaths and 539 hospitalizations in Hamilton.[49] The number of deaths in the Greater Toronto area believed to be caused by air pollution was comparable to that caused by lung cancer (1048) and stroke (1347). Sahsuvaroglu and Jerret[50] reported 374 deaths, 607 respiratory hospital admissions, and 2000 cardiac hospital admissions in Hamilton during 1997 due to air pollution.

In Delhi, India, Pande et al.[51] found increases of more than 20% in chronic obstructive pulmonary disease (COPD) and acute coronary events attributable to air pollution. Cropper et al.[52] found a significant relationship in Delhi between PM pollution and daily nontraumatic deaths, as well as deaths from certain causes (e.g., cardiovascular and respiratory diseases). On average, a 100 $\mu g/m^3$ increase in TSP was associated with a 2.3% increase in mortality. Although air pollution in Delhi appears to have less impact on mortality, the number of life-years saved per-death-avoided is greater in Delhi than in U.S. cities. In U.S. cities, PM has its greatest influence on daily deaths among people 65 years and older, whereas in Delhi the largest impact occurs in the 15–44 age group. This implies that, on average, for each avoided death associated with air pollution, more life-years would be saved in Delhi than in U.S. cities.

In Beijing, China, Xu et al.[53] found a significant association between SO_2 levels and daily mortality throughout the year. The mortality risk was estimated to increase by 11% with each doubling in SO_2 concentrations (averages were 120 and 67 $\mu g/m^3$ in 1998 and 2002, respectively). A significant association was also found between TSP and mortality by Xu et al.[53] Dong et al.[55] found a statistically significant association between air pollution levels and daily mortality during 1990 and 1991. The influence of TSP on patients with cardiovascular disease and of SO_2 on patients with respiratory disease was greater than that on other patients. The air pollutants were especially harmful to patients older than 65. Zhang et al.[56] observed statistically significant correlations between SO_4^{2-} concentrations and mortality from all causes, as well as on mortality because of cardiovascular disease, malignant tumors, and lung cancer. Zhang et al.[57] showed a significant association of the air quality index with mortality, especially in the winter and among those 55 years and older with COPD and other respiratory diseases. Similar findings, reported by Chang et al.,[58] showed an increase of ~20% in mortality from COPD for an SO_2 increase of 100 $\mu g/m^3$ and of ~3% in respiratory deaths for a TSP increase of 100 $\mu g/m^3$.

Xu et al.[54] collected 1990 data from a community-based hospital in Beijing to assess the association of air quality with daily nonsurgery outpatient visits, and found significant associations with both SO_2 and TSP levels. Chang et al.[59] also found significant associations between air pollutant concentrations and outpatient visits for colds, pneumonia, and bronchitis for children in Beijing from 1998 to 2000. Wang et al.[60] found a significant association with SO_2 and NO_2. Zhang et al.[61] attributed a decrease in the levels of vital capacity and max voluntary ventilation to high TSP and NO_x levels. Xu et al.[62] reported that long-term exposure to high levels of TSP and SO_2 in Beijing was correlated with significantly reduced pulmonary function in adults; the associations were stronger among smokers than nonsmokers. Exposure to TSP and SO_2, or to a more complex pollution mixture, appears to contribute to excess risk of preterm delivery in Beijing. In a prospective cohort study,[63] all pregnant women living in four residential areas of Beijing were registered and followed from early pregnancy until delivery. Xu et al.[63] found a significant dose-dependent association of gestational age with TSP and SO_2 concentrations.

In Santiago, Chile, Sanhueza et al.[64] found that PM_{10} has the strongest association with premature mortality, with lower associations for O_3 and SO_2. Using daily counts of nonaccidental deaths in Santiago from 1988 to 1996, Cifuentes et al.[65] found a significant association between mortality and PM levels, with finer particles being more important than coarse particles. The concentration of PAHs and the mutagenicity of airborne particles in Santiago have been investigated and compared with those in Tokyo.[66] Ochoa and Roberts[67] reported the estimated cancer risks posed by exposure to suspended PM in Santiago. Ilabaca et al.[68] investigated the association between $PM_{2.5}$ and hospital visits for pneumonia and other respiratory illnesses among children. These studies demonstrate the adverse effect of pollution on human health.

In São Paulo, Brazil, Saldiva et al.[69] found significant effects of PM on respiratory functions in children. An increase in the mortality of elderly people in São Paulo associated with high PM_{10} levels has also been documented.[70,71]

Visibility Impairment

The connection between air pollutants and visibility impairment is related mostly to $PM_{2.5}$ concentrations, but it is often accompanied by high levels of other pollutants.[72] Urban haze is the most commonly perceived effect of excessive concentrations. In Beijing, China, visibility is often low, in part because of the relatively high frequency of foggy days. Nevertheless, the sky overhead is almost always gray, even in the absence of fog or clouds. Bergin et al.[73] concluded that during June 1999, combustion-related particles rather than wind-blown dust were mainly responsible for visibility degradation. It is well documented that Asian sand storms and dust cause poor visibility during the spring.[74] Song et al.[75] developed regression equations to estimate visual range as a function of $PM_{2.5}$ mass concentration.

In Ontario, Canada, the visual range without the effect of anthropogenic PM is estimated to be between 86 and 120 km; visual range decreases to between 35 and 50 km in the presence of PM. These calculations were based on average 24-hr $PM_{2.5}$ or PM_{10} levels; the results vary with the season, changing PM concentrations, and relative humidity levels.[76]

In Santiago, Chile, the study of air pollution started around 1980, when researchers noticed unusually hazy days during winter. These studies were related to TSP and its chemical characterization.[77–81] Trier and Silva[82] measured the optical properties of PM in Santiago and found high extinction and absorption coefficients. Trier and Horvath[83] found high daily variability in the extinction coefficient, from 0.018 km^{-1} in the morning to 0.15 km^{-1} in the afternoon, attributing this result mainly to a change in the mixing height and finding a high correlation with TSP levels. Trier and Firinguetti[84] performed a time-series investigation of visibility. Horvath et al.[85] found high variability in optical absorption coefficient on a time scale of a few hours because of changes in meteorological conditions. Concentrations between 1.3 and 25 $\mu g/m^3$ of black carbon (BC) were estimated on the basis of observed light absorption. Gramsch et al.[86] reported a strong correlation between optical absorption coefficients and traffic patterns in Santiago. Maximum absorption coefficient often occurs during the morning rush hour (7:00–8:00 a.m.), with the lowest value found either early in the morning (3:00–5:00 a.m.) or in the afternoon (2:00–5:00 p.m.). The absorption coefficient also shows a strong seasonal dependence, with values 10–20 times higher in winter than in summer. Most of the absorption is attributed to BC, mainly from vehicle exhaust. Using a low-cost optical instrument, Gramsch et al.[87] compared the absorption coefficient with PM and carbon concentrations.

A "black cloud" has often appeared above the Nile Delta and Cairo, Egypt, during October.[88,89] After the rice harvest, farmers burn rice straw to clear fields for the next crop. There is a prevalent upper-air high pressure system over the Nile Delta during such episodes. Nighttime cloudless skies also contribute to a decrease in surface temperature, leading to a steep thermal inversion.[90] Aerial photoreconnaissance identified the locations and intensities of the emissions.[91] Straw building has been encouraged as an alternative use for rice straw that minimizes vegetative combustion.[92]

Regional Ecosystem Impacts

Acid and Fixed Nitrogen Deposition. The detrimental impacts of acids that form from SO_2 and NO_x emissions on sensitive lakes, streams, forests, and farmlands have been well documented.[93] A related issue involves fertilization effects caused by the deposition of airborne fixed nitrogen spp. (PM NH_4^+ and NO_3^{2-} and their gas phase precursors) to buffered soils and surface waters that are not susceptible to acidification. Combined with fixed nitrogen and phosphorous from fertilizer, animal waste, and human sewage sources, atmospheric deposition of fixed nitrogen can over-fertilize soils, lakes, streams, and estuaries, leading to changes in primary productivity and, potentially, to eutrophication.[94] Atmospheric nitrogen deposition can even affect the ocean by stimulating phytoplankton blooms.[95–97] High levels of fixed nitrogen deposition can have significant effects on ecosystem diversity, even when deposition receptor areas are not heavily acidified. For instance, Stevens et al.[98] report that British grasslands subject to long-term chronic levels of nitrogen deposition have significantly lower levels of spp. diversity than those exposed to lower deposition rates; at average deposition rates of 17 kg N ha^{-1} per year for central Europe, a 23% reduction in plant spp. was found.[98] As the number of motor vehicles in developing world megacities increases, NO_x emissions will increase dramatically;[99] consequently, the impact of fixed nitrogen deposition on downwind ecosystems can be expected to rise rapidly.

Photochemical Oxidant Damage. Photochemically produced oxidants and their precursors frequently produce high levels of O_3 and other oxidants that transport from one major city to the next, subjecting the intervening suburbs, forests, and agricultural areas to high oxidant exposures.[99,100] Exposure to O_3 and related photochemical oxidants is known to damage both native and agricultural vegetation.[100] O_3 damage may affect crop yields in agricultural areas impacted by emissions from major cities in China.[101,103] Model calculations predict semi-continental to continental-scale plumes of high summer O_3 associated with urban and industrial emissions from the urban complexes in the midwestern and eastern United States, western and central Europe, and East Asia.[104]

Gregg et al.[105] report greater plant growth in New York City compared with a rural environment and attribute the effect to the higher O_3 levels in the rural area. Fenn et al.[106] document the significant damage to forests surrounding the Mexico City air basin caused by exposure to high levels of photochemical oxidants, mainly O_3.

Photosynthetically Active Radiation. Recent model analyses demonstrate the impact of Asian megacity SO_2 emissions on regional pollution. High SO_2 and other gaseous precursors can result in high levels of fine PM, with absorption and scattering properties that significantly influence both the direct and diffuse components of photosynthetically active radiation.[107] In fact, the resulting haze over eastern China has decreased solar radiation reaching the surface since 1954.[108] Attenuation of photosynthetically active radiation by both atmospheric PM and by PM deposited on plant leaves may significantly impact the solar radiation available for photosynthesis in agricultural regions in China.[102,109]

Regional Climate Change

Emissions from megacities may also play a role in regional climate impacts. High levels of GHG associated with major cities[27] have a direct impact on IR radiative forcing globally.[110] Furthermore, the powerful but shorter-lived tropospheric O_3 will have a more pronounced regional effect.[104]

Fine PM can have a direct effect on short wavelength radiative forcing by scattering and/or absorbing solar radiation. Satellite observations show an albedo reduction because of absorbing aerosols and their impact on cloud absorbance over urbanized regions in China.[111]

Surface temperature records in urbanized regions of China[108,112,113] and India[113] show a measurable cooling since the 1950s. Analyses of meteorological data in heavily urbanized regions of China demonstrate significant downward trends in both sunshine duration (1% to 3% per decade) and max daily temperatures (0.2–0.6 °C per decade).[108,112] The observed cooling trends are consistent with the predicted effects of elevated soot levels in fine PM,[113] and are achieved despite a general warming observed for most of the globe over the same time period.

High PM loadings that increase the number of effective cloud condensation nuclei can also influence precipitation levels by lengthening cloud lifetimes and suppressing rain and snow as a result of nucleating more, but smaller, cloud droplets. Satellite observations show significant rainfall suppression downwind of major cities.[114] High PM loadings with a large fraction of absorbing soot particles are predicted to reduce cloudiness by absorptive heating of cloud particles,[115] although the impact on cloud cover may also be affected by the increased atmospheric circulation.[113]

Yet another consequence of long-range transport involves impacts on urban populations of sand, dust or smoke that originate beyond the urban centers, giving rise to episodic pollution events. For example, dust and sand storms that originate in the dry regions of northern China and Mongolia and blow across parts of China, the Korean peninsula, and Japan are now taking place nearly five times as often as in the 1950s. These dust storms are also growing in intensity, and occur during the spring months as cold air masses from Siberia whip deserts and soils eastward after the dry continental winter.[158] In April 2002, dust levels in Seoul—1200 km from their source—reached 2070 $\mu g/m^3$. The effects in Beijing are also striking.[159,160] Between 1994 and 1999, the Gobi Desert in China expanded by 52,400 km^2, moving closer to Beijing. Up to 400 million people are threatened by the fast-advancing deserts. Nearly 30% of China's land area is affected by desertification caused by over-farming, grazing, and deforestation. The annual direct economic losses are estimated to be around \$6 billion. China, Mongolia, Japan, and South Korea are pooling their efforts to reduce the impact. Backed by the U.N. Environmental Program, the Global Environment Facility, the Asian Development Bank, the U.N. Economic and Social Commission for Asia and the Pacific, and the U.N. Convention to Combat Desertification, they are setting up a monitoring and early warning system for dust and sand storms, which is aimed at standardizing data collection and sharing information throughout the region.

Global Pollutant Transport

Satellite, aircraft, and ground-based observations throughout the global atmosphere are confirming model simulations that air pollution can be transported over long distances, for example, from eastern Asia to the western United States, from North America to Europe, and from mid-latitudes to the Arctic.[116–120] Tropospheric oxidants, changes in precipitation chemistry, and reduced visibility are already significant environmental issues in much of the industrial Northern Hemisphere.[101,121,122] Globally, current levels of pollution-related tropospheric PM and O_3 are significant contributors to the atmospheric "greenhouse" radiation budget.[123–127] Long-term changes in global OH concentrations, and therefore in the atmospheric residence times of many gases, are a matter of great interest but remain highly uncertain.[128,129]

Recent field campaigns have studied pollutants in the remote troposphere,[130–133] the outflow from East Asia,[134–143] the Indian subcontinent,[143] and North America.[144–148] Several regional-scale studies have been carried out in the United States[149–153] and Europe[154–157] that demonstrated the enormous pollutant potential of major cites and "megalopolis" regions, as well as the fact that significant quantities of gaseous pollutants and fine particles can be transported and detected over intercontinental scales. These insights have erased the distinction between air quality (long thought to be a local- to regional-scale issue) and global atmospheric chemistry (focused on concerns about GHG-induced climate change, stratospheric O_3 depletion, and tropospheric oxidative capacity). It is now clear that the gaseous pollutants and fine particles dispersed from heavily polluted regions may have significant impacts on continental to global scales.[28,117]

However, to date, relatively few measurements have been carried out on the polluted outflow from megacities in tropical and subtropical latitudes. Given the high growth rates and rapid industrialization and motorization of these megacities of the developing world,[27] it is likely that regional and even intercontinental transport of pollutants at low latitudes will grow rapidly, posing an even greater challenge.

AIR QUALITY CASE STUDIES IN MEGACITIES

Air quality in nine urban centers is summarized below to identify similarities and differences among the problems that are important to megacities throughout the world. The combined effect of natural and anthropogenic emissions (e.g., industrial, vehicle exhaust, vegetative burning, cooking, and resuspended dust), topographic features, and meteorology result in significant environmental degradation.

South Coast Air Basin, Los Angeles, California

The Los Angeles metropolitan area is the second-most populated urban area in the United States, after the New York metropolitan area. The multi-county South Coast Air Basin (SoCAB) is bordered by mountains on the east and north, and by the Pacific Ocean on the west and south. The area of the basin is ~17,500 km^2 with a population of 16 million. During summer, the SoCAB is often under the influence of a large-scale subsidence inversion that traps a layer of cool marine air. Pollutants emitted from various sources are pushed inland during the day by an on-shore breeze. Approximately 10 million gasoline vehicles and 250,000 diesel vehicles travel in the SoCAB, which (in conjunction with other emitters) results in poor air quality.[161] PM_{10} has decreased over the last decade. Similarly, CO concentrations have been reduced. Peak O_3 for Los Angeles has decreased from 500 ppb in 1980 to less than 200 ppb in 2000, and the number of days above O_3 standard has declined since 1975. However, O_3 concentrations have recently leveled and may even be increasing as a result of population growth, additional vehicle kilometers traveled, and increased sales of low-economy sport utility vehicles.[162] Nevertheless, federal and/or state standards were exceeded during 2002 at one or more monitors for PM_{10}, $PM_{2.5}$, O_3, NO_2, and CO, particularly in the spring and summer.[162a] As other emissions are controlled, nonroad emissions of $PM_{2.5}$ are exceeding on-road emissions. Dust from paved and unpaved roads is also a large emitter. Motor vehicles are the largest source of VOCs, but solvent evaporation, an area-wide source, accounts for 20% of VOC emissions.[162b] NO_x emissions are dominated by on-road emissions because the SoCAB contains few large, stationary sources and requires stringent controls on those that remain.

Mexico City Metropolitan Area, Mexico

The MCMA attracted migrants from other parts of the country because of fast economic growth as the nation began to industrialize. The population grew rapidly, from 3 million in 1950 to 18 million in 2000, and occupied land increasingly far from the historic center. In the last half-century alone, the urbanized area of the region has increased by 13 times, from just 118 km^2 in 1940 to almost 1500 km^2 in 1995 (see Figure 1). The expansion pushed the city beyond the Federal District and into other municipalities of the State of Mexico, as well as into some parts of the State of Hidalgo.[11] Current and projected population growth stresses the urban environmental balance.[163–165] The MCMA population density of 12,200 inhabitants/km^2 in 2000 is among the largest in the world, but it is exceeded, for example, by the Asian cities of Mumbai, Kolkata, and Hong Kong.[166] Densities have also fluctuated in response to the sporadic efforts of the State of Mexico to control irregular settlement expansion.[166] Population growth has also generated extraordinary demand for transportation, health services, and housing.[167]

The MCMA lies in an elevated basin at an altitude of 2240 m above the mean sea level (MSL). The nearly flat basin covers ~5000 km^2 of the Mexican Plateau and is confined on three sides (east, south, and west) by mountain ridges, with a broad opening to the north and a narrower gap to the south-southwest. The surrounding ridges vary in elevation, with several peaks reaching nearly 4000 m, but the air basin is at 800–1000 m. Two major volcanoes, Popocatépetl (5452 m) and Ixtaccíhuatl (5284 m), are on the mountain ridge southeast of the basin. The metropolitan area is on the southwest side of the basin and covers ~1500 km^2.[167]

The MCMA's large population, 35,000 industries, 3.5 million vehicles, complex topography, and meteorology cause high pollution levels. The mountains, together with frequent thermal inversions, trap pollutants within the basin. The high elevation and intense sunlight also contribute to photochemical processes that create O_3 and other secondary pollutants. More than 40 million L of fuel consumed per day produce thousands of tons of pollutants. Air pollution is generally worst in the winter, when rain is less common and inversions more frequent.

Owing to the high altitude, MCMA air contains ~23% less oxygen (O_2) than at sea level. Consequently, internal combustion engines need to be carefully tuned to the proper O_2-to-fuel ratio to minimize inefficient combustion and increased emissions.[31,168] People at higher altitudes are more susceptible to respiratory ailments than those at sea level. More air must be inhaled for an

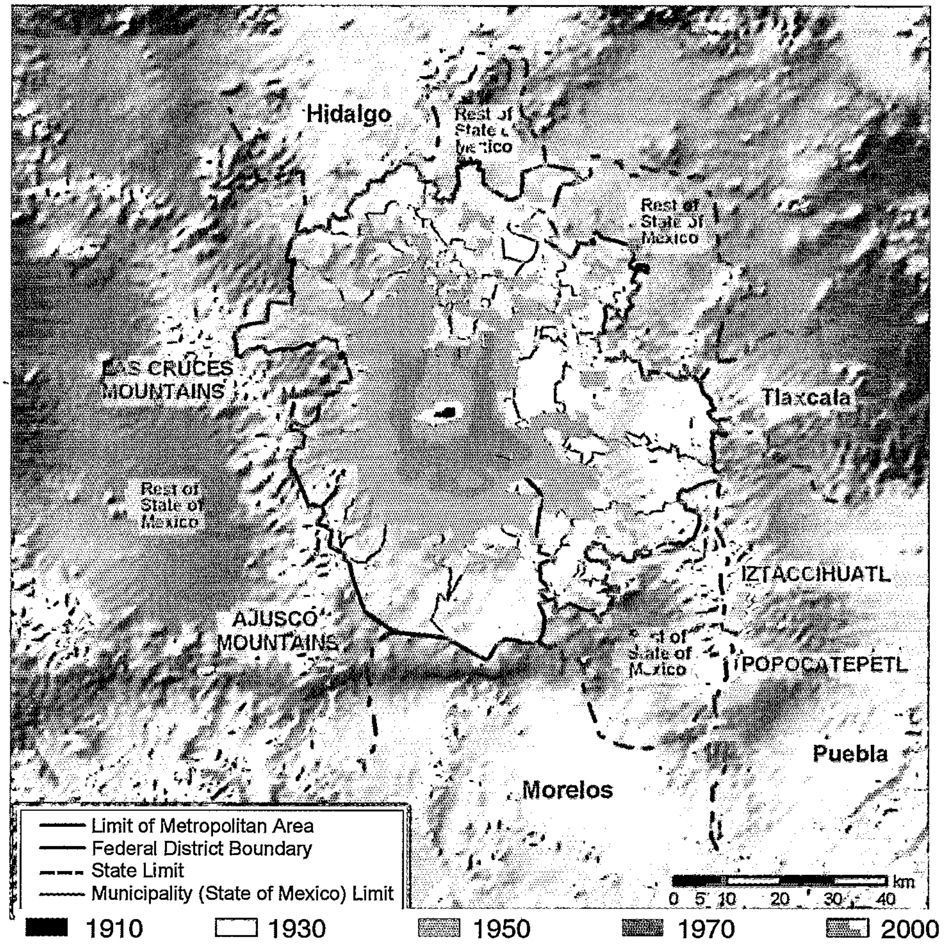

Figure 1. Topographical map of the Mexico City metropolitan area indicating expansion from 1910 to 2000.

equivalent amount of O_2 at high altitudes, which causes a higher dose of air pollutants.[169]

High O_3 is measured throughout the year because the subtropical latitude and high altitude are conducive to photochemistry. Anticyclone high pressure systems appear during winter, resulting in light winds above the basin and nearly cloudless skies. This leads to the formation of strong surface-based inversions at night that persist for several hours after sunrise. Strong solar heating of the ground generates turbulent mixing that erodes these inversions in the morning, producing deep boundary layers by the afternoon. Pollutants trapped below the inversion layer are then mixed within the convective boundary layer, which can reach altitudes of 4 km. There is sufficient time for O_3 formation in the morning before the development of the deep convective boundary layer because of high emission rates and intense solar radiation.

During the wet summer months (June to September), clouds inhibit photochemistry and rainfall removes many trace gases and PM; high O_3 episodes are less frequent. Near-surface northerly winds during the day may transport pollutants to the southwest, where O_3 concentrations are highest.[170] The relationship between meteorology and O_3 differs for different episodes.[171–173]

Air quality measurements for criteria pollutants are reported as IMECA units (*Indice Metropolitano de Calidad del Aire,* or Metropolitan Index of Air Quality), which are the ratio of a measured concentration to the air quality standard for each pollutant. A contingency program is triggered when the IMECA value exceeds a certain threshold, currently 240 IMECA, or ~280 ppb of O_3. During a contingency, the activity of polluting industries is reduced, vehicle circulation is restricted, and outdoor activities of children in primary schools are reduced.[174]

The most dramatic improvement in MCMA air quality resulted from the removal of lead from gasoline, which led to lower ambient and human blood levels. SO_2 concentrations are decreased after the reduction of sulfur content in diesel and heavy oil. The closing of a large oil refinery also improved air quality. CO concentrations have also decreased because catalytic converters are required on new automobiles. Inspection and maintenance of automobiles has also had an effect, although it is difficult to document.[175] Figures 2 and 3 show downward

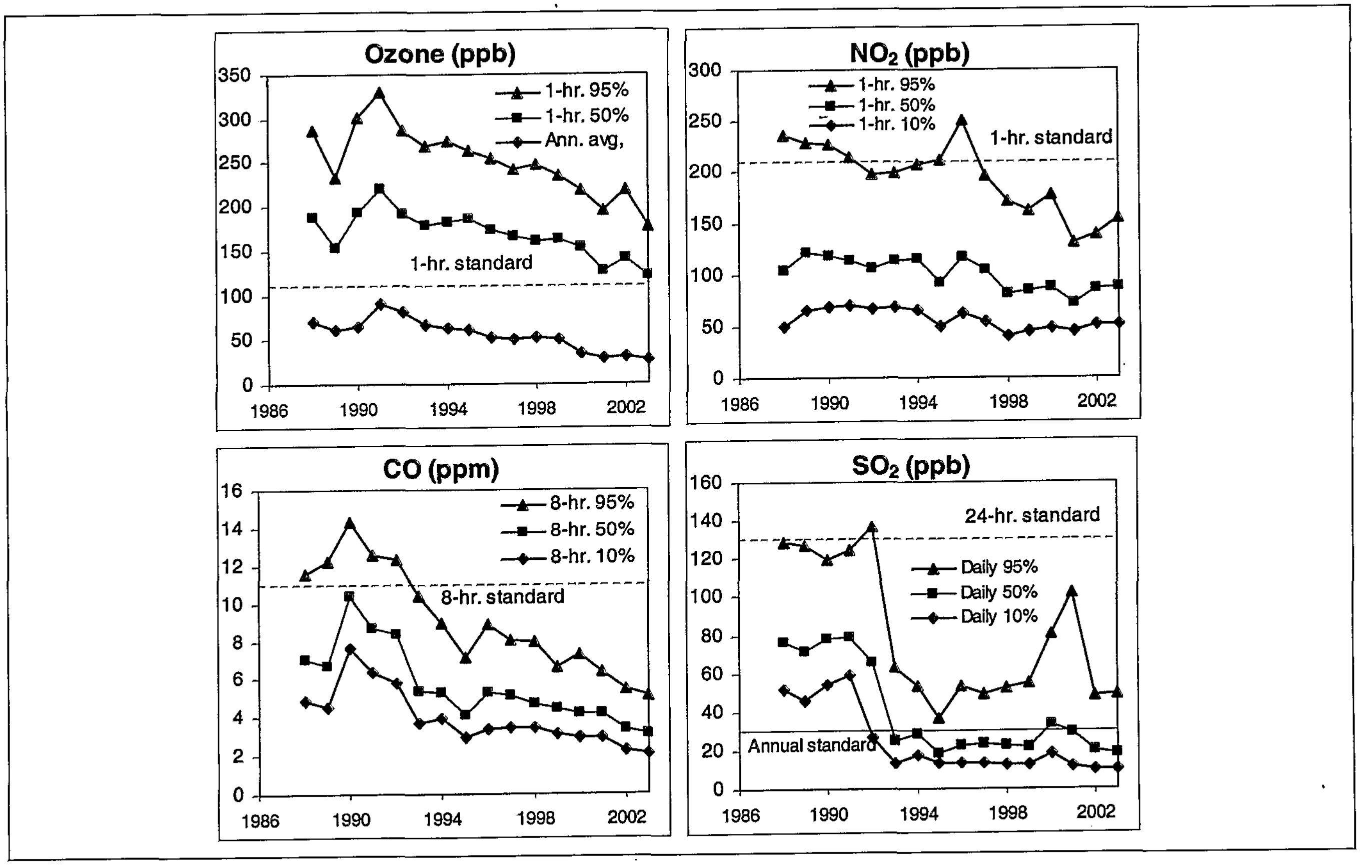

Figure 2. Trends in O_3, NO_2, CO, and SO_2 concentrations for the MCMA showing the averages of data at five representative RAMA sites. (*Source:* INE, 2004, Almanaque de Datos y Tendencias de la Calidad del Aire en Ciudades Mexicanas.)

trends for most pollutants, but PM_{10}, O_3, and NO_2 are not decreasing as rapidly as desired. The PM_{10} and O_3 standards are the ones most often exceeded in the MCMA.

Emission inventories have been developed in the MCMA since 1986.[176–178] VOC-to-NO_x M ratios are ~3:1 ppbC/ppbNO in the inventory, but they are 15:1 or higher in ambient air.[174] This is consistent with inaccurate emission models that were discovered in California in the early 1990s.[179–182] More recent emission inventories[33,183–187] have been developed. Table 4 shows the emission inventory for the year 2000. There are substantial differences in the emission inventory reported in the different years. These can be explained partly by changes in emissions over time, but they are more likely the result of differences in emission inventory methodology.[174]

Greater Toronto Area and Central Ontario Region, Canada

Ontario is Canada's most populated region and its third largest province, covering ~1 million km^2.[188] The Central Ontario Region (COR) extends from Long Point in the south, through the Niagara, Hamilton, and Waterloo Regions, to the east of the Greater Toronto area (GTA). The area is bounded by Lakes Ontario and Erie to the south.

In 2003, the total population of Canada was 31.6 million, with 12.1 million in Ontario, 7.3 million in the COR, and 5.4 million in the GTA.[189,190] The population growth rate of the COR is estimated to be ~1.5% from 2000–2010, with a population density of ~50 inhabitants/km^2. The GTA has an average population density of 3000–4000 inhabitants/km^2 with a max of 6700 inhabitants/km^2.[191]

The climate in the COR is one of the mildest of any region of Canada, which has contributed to the area's industrialization and habitation.[192] The region lies across a major storm track; high and low pressure systems passing over the area produce wide variations in meteorology. Moisture from the Great Lakes in fall and winter increases precipitation, while the latent heat of the Great Lakes protects the region from winter cold. In spring and summer, the cooler waters of the Great Lakes moderate the heat of the tropical air that approaches the area.[193]

Hourly measurements of $PM_{2.5}$, O_3, SO_2, NO_2, CO, and total reduced sulfur were used to estimate an air quality index. O_3 was responsible for almost all of the poor air quality hours recorded during 2001 in the COR. Since 1971, SO_2 and CO concentrations have decreased by more than 80%. NO_x concentrations have decreased by ~49% over the past 26 yr. Current concentrations of

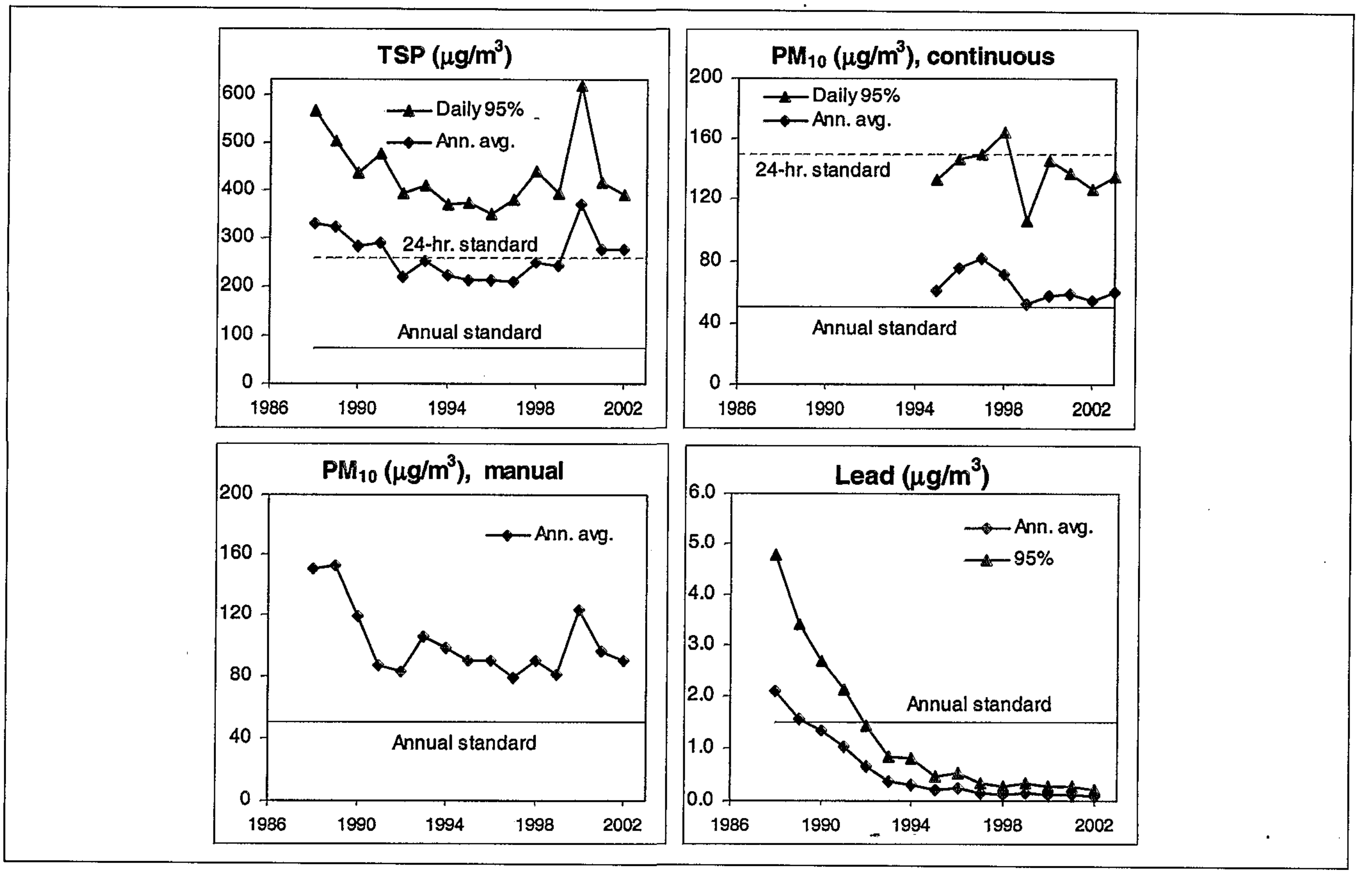

Figure 3. Trends in PM_{10}, TSP, and lead concentrations for the MCMA showing the averages of data at five representative RAMA sites. (*Source:* same as Figure 2.)

SO_2, NO_x, and CO do not exceed provincial and federal air quality criteria, but $PM_{2.5}$, PM_{10}, and O_3 are above the criteria. Though the average O_3 concentration varies over time, it shows a general increase from 1982–2001.

Table 4. 2000 MCMA Emission inventory by sector (tons per day).

	PM_{10}	$PM_{2.5}$	SO_2	CO	NO_x	CH_4	VOC	NH_3
Stationary sources	8	2	28	27	68	0	60	1
Area-wide sources	1	1	0	18	29	462	542	36
On-road motor vehicles	9	7	11	5479	370	31	513	6
Other mobile sources	6	5	1	52	61	1	20	0
Vegetation and soils	5	1	N/A	N/A	2	N/A	42	N/A
Total	28	17	40	5577	530	494	1177	42
Stationary sources	27%	9%	70%	0%	13%	0%	5%	1%
Area-wide sources	5%	8%	0%	0%	5%	93%	46%	84%
On-road motor vehicles	31%	45%	27%	98%	70%	6%	44%	15%
Other mobile sources*	20%	31%	3%	1%	11%	0%	2%	0%
Vegetation and soils	17%	6%	N/A	N/A	0%	N/A	4%	N/A

*Not including construction equipment and locomotives (included in Area-Wide Sources).
Source: 2000 Emission Inventory for the MCMA, http://www.sma.df.gob.mx.
Note: N/A = Not applicable; N/S = Not Significant; N/E = Not Estimated.

The COR contributes over 49% of the NO_x, VOC, and CO emissions, while the remainder originate elsewhere. Over 58% of NO_x and CO emissions in the COR are from mobile sources, while ~50% of PM and VOC emissions are attributable to area sources. The COR's proximity to the border makes it vulnerable to the long-range transport of pollutants from the United States.

Between January and November of 2003, there were 53 days with an Air Quality Index >31 in Toronto, and 14 (26%) of them were caused by $PM_{2.5}$. There were 77 such days in Hamilton, 46 (60%) of which were caused by $PM_{2.5}$.[194] Elevated O_3 concentrations are generally recorded on hot, sunny days from May to September, between noon and early evening, with much of the O_3 originating from cross-boundary transport. For the same land use, O_3 levels in southern Ontario decrease from southwest to northeast because of the combination of trans-boundary sources and synoptic meteorology.

In 2001, transportation and fuel combustion accounted for more than 50% of $PM_{2.5}$ emissions in Ontario. More than half of the elevated $PM_{2.5}$ in Ontario and as much as 90% of the $PM_{2.5}$ in the border cities may be transported from the United States.[195] NO_x concentrations did not change significantly from 1991–2001, but there has been a general decrease from 1970.

The Ontario transportation sector emitted ~63%[195] of the NO_x and 85% of the CO, with the highest NO_2 level of 27.1 ppb recorded in Toronto, based on estimates in 2001. The max annual average of CO was found in Toronto, while the max 1-hr average was recorded in Hamilton. Between 1992 and 2001, the annual average CO concentration (based on nine sites in Ontario) did not show a trend (0.6–0.9 ppm), but the composite average of the 1-hr maxima decreased by 29%. These CO reductions occurred despite a 17% increase in vehicle-kilometers traveled over the same 10-yr period. The transportation sector accounted for ~29% of anthropogenic VOC emissions in Ontario in 2001, while general solvent use accounted for 24%.[195] Benzene, toluene, and o-xylene decreased from 1993–2001.

The major SO_2 emission sources in the COR and across Ontario are metallurgical industries such as copper smelters, and iron and steel mills.[196] Other major sources include utilities, petroleum refineries, and pulp and paper mills. Lesser sources include residential, commercial, and industrial heating. In 1995, point sources contributed ~71% and 86% of SO_2 emission in the COR and Ontario, respectively. Similarly, in 2001, ~83% of the SO_2 emissions in Ontario were from smelters, utilities, refineries, and the primary metal sectors. Historically, the highest SO_2 concentrations in the COR have been recorded in the vicinity of large local industrial sources. Lee et al.[197] found that long-range transport contributes to the SO_4^{2-} pollution within the COR. The implementation of regulations on smelting operations and the Ontario government's "Countdown Acid Rain" program resulted in a significant decrease of SO_2 emissions from 1991 to 1994, and it has remained constant.

Delhi, India

Delhi, the capital city of India, is located in the northern part of the country at an elevation of 216 m above MSL, with an area of 1483 km^2.[198,199] The Yamuna River and the terminus of the forested Aravali hill range are the two main geographical features of the city. The average annual rainfall in Delhi is 700 mm, three-fourths of which falls in July, August, and September.[200]

In 1901, Delhi was a small town with a population of only 0.4 million people. Its population started to increase after it became the capital of British India in 1911. As India achieved independence in 1947, a large number of people migrated from Pakistan and settled in Delhi. The population growth rate was 90% in the decade 1941–1951. Delhi's population increased from 4 million in 1971 to ~14 million in 2001.[200] In 1965, Delhi had a cloudless, bright blue sky; by the 1990s, haze was common and pollutant levels were high, especially during winter.[201] During the same period, the number of vehicles increased more than 19-fold, from 0.18 million to 3.46 million.[202] About two-thirds of the registered motor vehicles are two-wheeled scooters with two-stroke engines. The number of small-scale industrial units grew from 8200 in 1951 to 120,000 in 1996.[200]

Delhi's climate is semi-arid, with an extremely hot summer, average rainfall, and cold winters. The annual average temperature is 25.3 °C, while average monthly temperatures range from 14.3 °C in January to 34.5 °C in June.[203] During winter, frequent ground-based temperature inversions restrict atmospheric mixing; coupled with traffic emissions, this leads to high pollution events in Delhi.[203] During summer, large amounts of wind-blown dust carried by strong westerly winds from the Thar desert result in elevated PM.[199] These dust storms are followed by the monsoon season (July to mid-September), which is the least polluted because frequent rains wash out pollutants. The prevailing wind in Delhi is northwesterly, except during the monsoon season, when it is southeasterly,[204] causing spatial and seasonal variations in the pollution profile.

Nine ambient air quality monitors operate in Delhi,[205] including five industrial and four residential sites.[206] Most of the monitoring stations measure TSP, SO_2, and NO_2. PM lead, benzo-(a)-pyrene, and O_3 are also measured regularly at a major traffic intersection.[205,207]

Figure 4 shows trends for several pollutants. Annual averages of SO_2 and NO_2 often exceeded national standards of 15 μg/m^3 from 1994 to 2003. In 1997, mean 24-hr NO_2 levels exceeded the national standard of 30 μg/m^3 at 8 of 18 locations.[208] Further, annual and monthly averaged TSP levels[205] have almost always exceeded the national standards. While ambient SO_2 levels show a decreasing trend in Delhi (as expected after the introduction of low-sulfur fuel), NO_2 concentrations are increasing since 2001. Table 5 shows that ambient CO concentrations in Delhi have consistently violated the CO standard of 2000 μg/m^3 for residential areas. During 1997, O_3 levels were 150–200 μg/m^3 for 1-hr and 100–200 μg/m^3 for 8-hr averages.[206] Varshney and Aggarwal[198] and Singh et al.[199] observed 1-hr average O_3 concentrations exceeding the prescribed WHO standard of 100 μg/m^3 at various locations in Delhi. Compared with other large Indian cities such as Mumbai, Chennai, and Kolkata, the accumulation of air pollutants in Delhi during winter is more critical.[203]

Several emission inventories have been developed for Delhi.[202,209–217] Table 6 shows vehicular emissions in Delhi and their increases relative to base year 1990–1991. Within the past decade, emissions were doubled for SO_2, and increased ~6-fold for NO_x, CO, and HC, and nearly 12-fold for TSP.

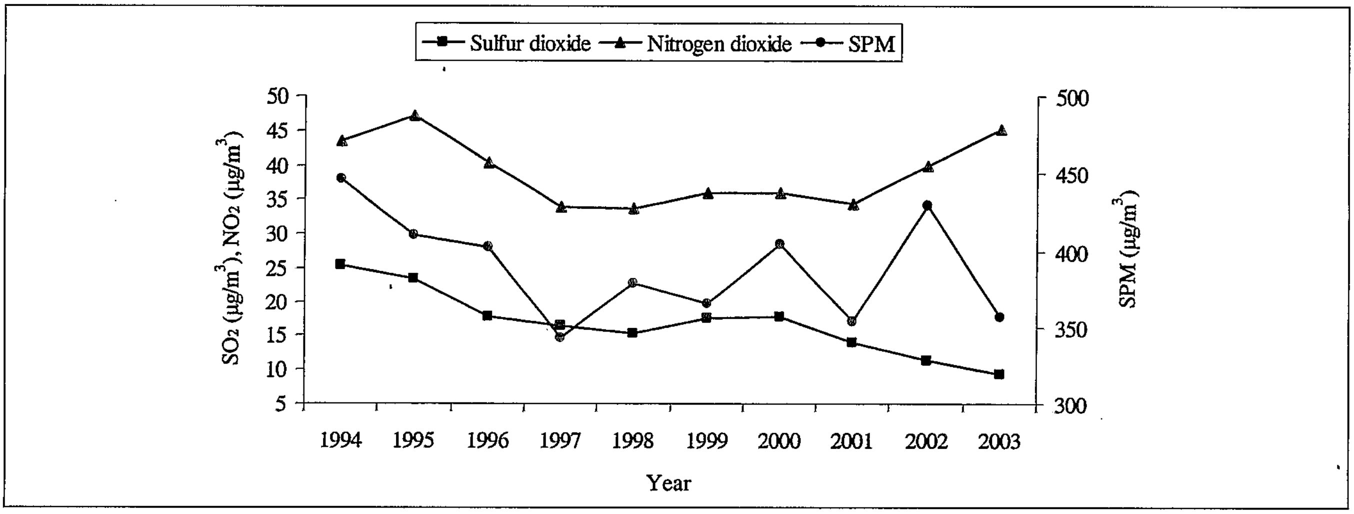

Figure 4. Averaged annual ambient air quality trends (1994–2003) in Delhi.

Beijing, China

Beijing lies in the North Plain of China. Another large city, the Tianjin Municipality, is located to the east of Beijing. Beijing covers 16,810 km^2 and slopes from the northwest to the southeast. Mountains form the north, west, and northeast boundaries of Beijing, while to the southeast is a plain that inclines gently toward the coast of the Bohai Sea. Thus, the region behaves like a dustpan that accumulates air pollutants. Located in a warm temperate zone, Beijing has a semi-humid climate with four distinctive seasons: short springs and autumns, and long summers and winters. Average temperatures range from −6.4 °C in January to 29.6 °C in July, with an annual precipitation of 371 mm.

Beijing's population in 1970 was 8.3 million;[25] at the end of 2000, it had a registered population of 11 million, in addition to ~3 million temporary residents. The city is considering restrictions to its future growth. The urban district area will be limited in size to 300 km^2, and more than 20 towns will be built to relocate industries and population. At the same time, roads will be paved, green belts will be built along the second and the third ring roads, and several gardens will be set up on the outskirts of the city.

Table 5. Ambient CO trends (1995–2000) in Delhi.

Location of Measurements	Annual Average CO Concentrations (μg/m³)					
	1995	1996	1997	1998	1999	2000
Residential area average (Siri Fort)	No data	No data	3177	3340	3578	2376
Traffic junction average (ITO)	3916	5587	4810	5450	4241	4686

Source: CPCB[205]

Surrounded by heavy industry, Beijing has benefited from fast economic development since the state policy of reform and opening to the outside world became official in late 1978. A rapid rise of high-tech industry has also contributed to its economic development. Over the past 10 yr, urban construction has flourished, with tall buildings now standing shoulder to shoulder around the second ring road, thus slowing the dispersion of air pollutants. In 2002, the GDP was 361 billion yuan, and the per capita GDP was 32,600 yuan (about U.S. $3800).[223]

The main air pollutants in Beijing are TSP/PM$_{10}$, O$_3$, SO$_2$, NO$_x$, and CO. Table 7 shows that pollutant levels have generally decreased from 1998–2002, except for NO$_x$, as expected because of fuel switching from coal to oil.

Beijing is the city with the largest motor vehicle population in China. In the warm months, 55% of the NO$_x$ emissions and 61% of the CO emissions come from vehicle exhaust. In 1997, O$_3$ concentrations exceeded the national standard of 160 μg/m^3 for 71 days between April and October. Max O$_3$ concentration was 346 μg/m^3, more than double the standard. As the motor vehicle population reached 1.35 million in 1998, O$_3$ concentration exceeded the standard on 101 days, 82% of which occurred between June and September, with a max of 384 μg/m^3.

Table 6. Vehicular emissions (tons per day) in Delhi.

Pollutant	SO$_2$	TSP	NOx	CO	HC
1990–91	6–10	1–19	44–139	243–492	82–200
1995–96	14–15	26–28	120–397	373–781	123–493
2000–01	18	35–196	261–860	447–4005	156–1542
Average decadal increase factor	2.2	11.6	6.1	6.1	6

Source: Gurjar et al.[202]

Table 7. Annual mean concentrations (μg/m^3) of air pollutants in Beijing 1998–2002.

Year	SO_2	NO_2	PM_{10}	TSP	CO
1998	120	74	Not measured	378	3.3
1999	80	77	180	364	2.9
2000	71	71	162	353	2.7
2001	64	71	165	370	2.6
2002	67	76	166	373	2.5
Change in the 1998–2002 period	−44.2%	+2.7%	−7.8%	−1.3%	−24.2%

Source: http://www.bjepb.gov.cn.

Elevated PM concentrations have been found in Beijing. Shi et al.[224] reported some PM_{10} levels over 400 μg/m^3 (weekly average), 655 μg/m^3 (12-hr average), and 230 μg/m^3 (annual average). The annual average $PM_{2.5}$ concentration was 106 μg/m^3, which is approximately seven times larger than the U.S. annual National Ambient Air Quality Standard (NAAQS) of 15 μg/m^3. He et al.[225,226] measured an annual average $PM_{2.5}$ concentration of ~120 μg/m^3, with a weekly $PM_{2.5}$ concentration ranging from 37 to 357 μg/m^3. Bergin et al.[73] reported a daily average value for $PM_{2.5}$ of 136 ± 48 μg/m^3, which is twice the 24-hr U.S. NAAQS of 65 μg/m^3. Daily averages were 513 ± 212 μg/m^3 for TSP and 192 ± 47 μg/m^3 for PM_{10}, respectively.[73]

Major anthropogenic SO_2 sources are fossil fuel and coal combustion, the metallurgical industry, and the manufacturing of sulfuric acid. Between 1994 and 2002, SO_2 emissions decreased from 360 to 190 million tonnes. The main VOC sources are fossil fuel combustion (mainly in stationary stoves and motor vehicles), solvent use, paint applications, degreasing operations, dry cleaning, chemical production, and asphalt.[227] Ispoprene and monoterpenes were the main biogenic emissions, accounting for 48% and 22% of VOC emissions, respectively.[228] Measurements of VOCs between 1995 and 1999 indicate that benzene, toluene, ethylbenzene, and xylene (BTEX) were the main constituents of ambient VOCs in Beijing. The BTEX concentrations have increased considerably in recent years as a consequence of the rapid growth in the transportation and industrial sectors: in 1999 ethylbenzene increased by 220%, xylenes by 133%, and toluene by 91%.[229]

Table 8. Emission and ambient concentration contribution to PM_{10}, SO_2, and NO_x in Beijing urban districts in 1999 (%).

Source	PM_{10} Emission	PM_{10} Concentration	SO_2 Emission	SO_2 Concentration	NO_x Emission	NO_x Concentration
Industry	26.9	21.6	23.9	39.6	25.9	13.2
Heating	10.2	6.4	26.2	48.1	11.3	8.1
Civil	4.1	8.6	1	4	1.5	2.7
Traffic	8.2	13.8	—	—	34.5	73.6
Fugitive dust	39.5	48.7	—	—	—	—
Other sources	11.1	0.9	48.9	8.3	26.8	2.4
Total	100	100	100	100	100	100

Source: He et al.[230,231]

Table 8 shows the contribution of different sources to the emissions and ambient concentration of PM_{10}, SO_2, and NO_x in Beijing. PM_{10} is largely contributed by fugitive dust and industries; major sources of SO_2 are heating and industries, while traffic and industrial activities were the most important sources of NO_x.[230,231]

Santiago, Chile

Santiago, the capital of Chile, occupies ~135 km^2 and has a population of 5.3 million, which represents ~40% of the Chilean population. It is located in central Chile at an elevation of 520 m above MSL in the middle of a valley and is surrounded by two mountain ranges: the Andes Mountains and the Cordillera de la Costa. The climate in Santiago is mediterranean: summers are hot and dry with temperatures reaching 35 °C, while winters are more humid, with temperatures ranging from a few degrees above freezing to 15 °C. The unique topographic and meteorological patterns restrict the ventilation and dispersion of air pollutants within the valley, making Santiago particularly susceptible to poor air quality, especially during the winter (April to September).

Air pollution in Santiago results from a growing economy, rapid urban expansion, industrial sources, and an increasing rate of automobile use. Although the city has a state-run underground metro system, cars and trucks are becoming increasingly popular as the number of private automobiles in Santiago has increased to nearly 1 million. The city also has a large fleet of diesel buses that are poorly maintained and contribute substantially to air pollution.

Santiago ranks as one of the most polluted cities in the world and frequently confronts air-quality alerts and pollution emergencies. Since the early 1990s, the Chilean government has taken numerous steps to mitigate air pollution levels. These steps include an air pollution alert system-based on the max PM concentration in the city's air, and a rotating schedule that restricts the number of cars allowed on the streets on given days. One of the commitments undertaken by the current administration is to modernize the metropolitan region's public transportation system. Santiago has also partnered with U.S. Department of Energy Clean Cities International program to increase the use of alternative fuels in Santiago's public transportation sector.

One of the first studies of air quality in Chile was a comparison of the pollutant levels in Caracas, Venezuela, and Santiago, and the relationship of those levels to meteorological conditions.[80] Subsequent studies measured daily gaseous pollution levels,[232] the suspended particles,[81] and their size distribution.[79] Contaminants in rainwater[77] and elemental composition of TSP[233a] were also reported. Trier and Silva[82] found high extinction and absorption coefficients in Santiago, whereas Horvath et al.[233b] compared outdoor and indoor soot concentration.

In the 1990s, the number of publications related to air quality increased considerably. Romero et al.[234] discussed changes in land use, seasonal and daily weather cycles, and geographical and cultural factors that contribute to pollution. Rappengluck et al.[235] discussed the evolution of photochemical smog, which included O_3, NO_x, and CO, peroxyacetyl nitrate, and nonmethane HCs, and estimated that over 50% of the max daytime O_3 and almost all peroxyacetyl nitrate are formed within the urban plume. Kavouras et al.[236] reported a PM source apportionment study in Santiago. Based on the loadings of PAHs and n-alkanes, four factors (sources) were identified: high-temperature combustion, fugitive emissions from oil residues, biogenic sources, and unburned fuels. The results of this study are in good agreement with the estimates made by Chen et al.[237] Further study by Kavouras et al.[238] reported source contributions of PAHs in several cities in Chile and compared the results with Santiago. Tsapakis et al.[239] reported on-road and nonroad engine emissions as the main sources of carbonaceous aerosols in fine particle samples in Santiago.

Air quality forecasting is an important subject in Santiago because during winter restrictions are placed on city activities according to the predicted pollution levels. Rutlland et al.[240] described the meteorological conditions that trigger high pollution episodes. Air pollution potential is defined based on various meteorological episodes. The results are used extensively for air quality forecasting in Santiago.

Perez et al.[241] developed a neural network model to predict $PM_{2.5}$ concentration several hours in advance. Prediction errors vary from 30% for early hours to 60% for late hours. Silva et al.[242] extended the model to predict PM_{10}. Concentrations of NO and NO_2 in Santiago were predicted with meteorological variables using persistence, linear regression, and a multilayer neural network.[243]

Jorquera et al.[244] estimated the trends and impacts of public policies on air quality levels using data from 1989–1998. The yearly decreases in PM_{10} concentrations were found to lie between −1.5 and −3.3%, while the decrease for $PM_{2.5}$ was between −5 and −7%. A box model approach was employed to assess the contribution of different economic activities to air pollution levels. The approach was applied to SO_2, NO_x, and CO, including explicitly the seasonal behavior of meteorological variables. The results show that dispersion conditions in the fall and winter are 20–30% of the summertime values, explaining the poor air quality in those seasons. Older cars and diesel vehicles contribute more than half of the NO_x and CO emissions. Ambient SO_2 concentrations are largely dominated by stationary sources.[245] The relative importance of mobile sources to $PM_{2.5}$ levels has doubled in the last decade, whereas stationary source contributions have been reduced to half the value of the early 1990s.[246]

The possibility of building a model for SO_2 forecasting has been investigated by Perez[247a] with persistence, linear regression and a three-layer neural network model. The best fit is obtained with a neural network that employs SO_2 concentrations every six hours on the previous day plus the forecasted meteorological variables as input. Using an index of multivariate effectiveness, Silva and Quiroz[247b] found that the air quality-monitoring network can be optimized by excluding the least informative station with respect to the variables under study, which were PM_{10}, O_3, SO_2, and CO.

The role played in regional and global climate by the extensive and persistent deck of stratocumulus at the west coast of subtropical South America was studied by Garreaud et al.[248] The characteristics of the coastal-low episodes along the subtropical west coast of South America were also investigated.[249] The mean structure and evolution were determined using a composite analysis of 57 episodes during 1991, 1993, and 1994. In addition, Garreaud[250] studied the characteristics of cold air incursions over subtropical South America.

São Paulo, Brazil

São Paulo is ~60 km from the southeast coast of Brazil, at an elevation of 800 m above MSL. The Greater São Paulo area has 18 million inhabitants in 39 municipalities covering ~8000 km^2, two-thirds of which are urbanized.

The metropolitan area is home to a strong industrial base, which is responsible for ~16% of Brazil's gross national product. In addition, vehicle population has doubled in the last decade, reaching 3.5 million; mass transport is not efficient and covers only a small area of the city. A significant fraction of the bus and automobile fleet is more than 10 yr old, with high emission factors. The fuel used in Brazil is mostly gasohol (gasoline with 23% ethanol), and a small fraction of the automobile fleet runs on pure ethanol. As a consequence, the atmosphere is heavily loaded with aldehydes, in particular acetaldehyde and formaldehyde (HCHO).[251,252] Concentrations of HCHO in downtown São Paulo range from 4–8 ppb, while acetaldehyde concentrations range from 6–11 ppb.[251,254] O_3 formation rates are significantly affected by these high aldehyde concentrations. Evaporative emissions from gas stations and vehicles are also significant. Automobiles with low emission factors that can run with any mixture of gasoline/alcohol started to be produced in 2003, and these are expected to improve air quality.

São Paulo suffers from severe air pollution from PM_{10}, O_3, and aldehydes. During winter, shallow inversion layers trap pollutants within the 200–400 m range for several days, resulting in elevated pollutant concentrations.[253] Ambient SO_2 concentrations are low, and most of it comes from the sulfur content in diesel fuel. The average CO concentrations are in the 2–4 ppm range, but in some heavy traffic areas the 8-hr averages exceed the air quality standard of 9 ppm. As measured at the 33 monitoring stations within the city, the range of NO_2 values is from 25–75 $\mu g/m^3$, well below the annual air quality standard of 100 $\mu g/m^3$.[254]

The 24-hr PM_{10} standard of 150 $\mu g/m^3$ is frequently exceeded, mostly during wintertime; average annual PM_{10} concentrations reached 75 $\mu g/m^3$ at some stations. Vehicular emissions are responsible for ~35% of PM_{10}, while industrial emissions account for ~25%, re-suspended dust ~20%, secondary sulfates ~10%; other small sources such as wood combustion, garbage incineration, metallurgical emissions, marine aerosol, etc., account for the remaining PM_{10}.[255–257] Secondary organic aerosol is an important fraction of $PM_{2.5}$, as is BC, which accounts for ~11%.

Bogotá, Colombia

Bogotá is the capital of Colombia and also its administrative and political center. In 2003, the population was 6.5 million, with a growth rate of 2.4% per year. The population density is ~3700 inhabitants/km^2.[258] The city's elevation is 2640 m above MSL on the highest plateau in the Colombian Andes, and occupies an area of 1732 km^2. Mountains on the east and south border the city; most of the urban area is flat, but there is some development in hilly areas in the southern part of the city.

Bogotá has a high-mountain tropical climate, with an average temperature of 14 °C. The dry season is December to March, and the rainy seasons are April to May and September to November. During August, there are usually heavy winds from the north. The weather is strongly influenced by El Niño.[258] Bogotá has ~900,000 private vehicles,[259] and a large number of highly polluting small industries (e.g., brick and quicklime manufacturing).

Bogotá has an air quality monitoring network (DAMA, Departamento Técnico Administrativo del Medio Ambiente) composed of nine stations. In addition to meteorological parameters, the network monitors TSP, PM_{10}, O_3, SO_2, NO_2, and CO. Between 1998 and 2002, the air quality network showed reductions in average annual concentrations of CO (−28%), NO_2 (−13%), and O_3 (−6%).[260] However, there was a 12% increase in PM_{10} and a 15% increase in SO_2 during the same period, with both pollutants showing noncompliance with local standards in 2002.[260]

Bogotá operates the successful TransMilenio Program. The bus rapid transit (BRT) system deployed in this program has resulted in travel time and operational cost reductions, as well as in a decline in traffic accidents.[261] Furthermore, air pollutant emission reductions have been achieved as a consequence of replacing an obsolete transit fleet, running more efficient bus transit operations, and shifting to more efficient transportation. Hidalgo[261] estimated the emission reductions from baseline levels because of the implementation of the TransMilenio Program. The estimate assumes the replacement of 1500 obsolete buses by 709 new buses, and a 26% reduction in auto trips.

Cairo, Egypt

Cairo, the capital of Egypt, is the largest city in Africa and the Middle East. It is located on the banks and islands of the Nile in the north of Egypt. The population of the Cairo urban agglomeration is 10.8 million, and is projected to reach 13.1 million by the year 2015.[1] Greater Cairo consists of Cairo, Giza, and Kalubia, and has a population of more than 20 million.

Cairo has a hot, dry desert climate. The monthly average temperature ranges from 14 °C in January to 29 °C in July. The max daily temperature can reach 43 °C in the summer. The average annual rainfall is only 22 mm, and the monthly max of ~7 mm occurs in December.

Although Cairo itself is only ~1000 yr old, parts of the metropolis date back to the time of the Pharaohs. The first Muslim settlement of Egypt was Al-Fustat, now a part of old Cairo. Cairo was conquered and controlled by a host of invaders, including the Mamluks, the Turks, and Napoleon Bonaparte of France. In the nineteenth century, one of the city's rulers, Khedive Ismail (1863–1879), sought to transform Cairo into a European-style city. This, along with the British occupation of Cairo in 1891, led to the development of new suburbs for affluent Egyptians and foreigners. By the turn of the century, most commercial activity was also moving into modern Cairo. The urbanization of the Greater Cairo area has been facilitated by an extensive flood control program and improved transport facilities developed over the past 30 yr. Cairo is the only city in Africa with a metro system.

Although the conservation of agricultural land has long been a priority of Egyptian development policy, much of the critically needed arable land in Cairo is being lost to urban development, half of which is illegal; the remainder is planned developments in the desert. Cairo has about one-third of Egypt's population and 60% of that nation's industry. It is one of the world's most densely populated cities, with one of the lowest provisions of road space per capita and a dramatic growth in the number of private vehicles. The government has exacerbated this situation by spending on bridges and overpasses, and by heavily subsidizing fuel, all of which promotes the use of private vehicles.

Emissions from industry and motor vehicles cause high ambient concentrations of PM, SO_2, O_3, NO_x, and CO in Cairo.[263] However, continuous measurements of these pollutants need to be conducted to establish the extent of the air quality problem.

Lead levels in Cairo are among the highest in the world, and are estimated to cause between 15,000 and 20,000 deaths a year, according to a 1996 report by the Egyptian Environmental Affairs Agency. PM lead concentrations ranged from 0.5 $\mu g/m^3$ in a residential area to 3 $\mu g/m^3$ at the city center, and the high lead levels were mainly attributable to motor vehicle emissions.[263] Sturchio et al.[262] measured lead and TSP at 11 sites; the concentrations ranged from 0.08 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively, at one site to over 3 $\mu g/m^3$ and 1100 $\mu g/m^3$, respectively, at the city center. Because Cairo began to phase out leaded gasoline in 1996, Sturchio et al.[262] concluded that local lead smelters emitted the majority of atmospheric lead. Rodes et al.[264] measured $PM_{2.5}$ and PM_{coarse} concentrations during a source apportionment study in Cairo from 1994 to 1995. The annual average PM_{10} concentrations exceeded the 24-hr U.S. NAAQS of 150 $\mu g/m^3$ at almost all sampled sites.

To develop and implement a pollution control strategy in Cairo and to reduce the health impact of air pollution, the Cairo Air Improvement Project (CAIP) was established.[264] Source attribution studies were performed as part of this project to assess the impact of various sources (e.g., lead smelters, motor vehicles, oil combustion, vegetative burning, geological material) on ambient pollutant levels.[266]

The design of the CAIP network, and ambient PM and lead measurement results, have been reported by Labib et al.[267] For the period 2000–2001, high levels of PM were reported for all sites, with annual average PM_{10} and $PM_{2.5}$ levels generally exceeding 150 $\mu g/m^3$ and 75 $\mu g/m^3$, respectively. Max PM levels were observed in the highly industrialized areas of the city. In spite of the introduction of unleaded fuel, ambient lead remains a major problem. For 2000, the annual average PM_{10} and $PM_{2.5}$ lead levels in most contaminated sites exceeded 20 $\mu g/m^3$. Observed levels were reduced by ~40% in 2001 through CAIP-initiated efforts.

To determine the sources of pollution episodes, intensive PM_{10}, $PM_{2.5}$, and VOC monitoring was carried out at six to eight sites in the greater Cairo area during a fall and winter period in 1999, and during a summer period in 2002.[266] Crustal components Si, CA, Fe, and Al were significant at all sites. The majority of crustal material was in the PM_{coarse} fraction. OC and elemental carbon were major components of PM at all sites. The likely sources include mobile emissions, open burning, and fossil fuel combustion. The highest average VOC concentrations were found at a mobile-source dominated site: 2037 ± 1369 ppb during the fall and 1849 ± 298 ppb during the winter.[266] The temporal variations of VOCs were consistent among the six sites during winter.

The most abundant VOCs were isopentane and n-pentane, which are associated with evaporative emissions from motor vehicles; C2 compounds (e.g., ethane, ethene); propane; isobutene; and n-butane, which comes from compressed natural gas (CNG) and liquefied petroleum gas (LPG). Methyl tertiary-butyl ether—a gasoline additive—toluene and benzene were also abundant.

AIR QUALITY ASSESSMENT TOOLS FOR MEGACITIES

Air quality management in megacities takes place in four stages.[268] The initial stage of problem identification recognizes that existing air quality is unacceptable and determines the causes of excessive levels. Having determined the type and severity of the problem, policy is formulated to solve it. Implementation of policy follows, in which the strategies to reduce emissions are enacted and enforced. Assuming that the problem was correctly identified and that appropriate policy has been formulated and successfully implemented, the control situation is achieved. Although the initial problem might have been resolved, management capabilities are required to ensure that the control situation persists. Changes in emissions affecting the urban area and a more precise definition of the problem may identify new air quality issues to be resolved, and the management cycle is initiated again. Continued monitoring is needed for problem definition and maintaining the control situation. Throughout each cycle it is essential to ensure that the public remains informed of the status of their air quality.

The design of emission controls requires detailed information on the status of the air quality (provided by monitoring networks) and the principal sources of pollution and their location, as characterized by the emission inventory. Combining the information from monitoring and emission estimates with knowledge of dispersion characteristics for the city and chemical transformations of pollutants enables air quality models to be developed. Such models are powerful tools for air quality managers, but there is no perfect model that can be applied to formulate an effective air quality management strategy. It is important to consider an overall view of urban air quality rather than to focus on single-pollutant or isolated problems.

Air Quality Monitoring Networks

Ambient monitoring at representative exposure locations is carried out to represent the effects from the aggregate of all emissions. Monitoring is conducted to examine excessive pollutant levels, determine compliance with standards, identify and quantify source contributions, determine exposures, evaluate the effectiveness of emission reductions, and perform air quality modeling.[269] Data quality objectives, network design and management structures, monitoring locations, instrumentation, operation and maintenance of systems, quality assurance and control procedures, data review, data validation, and data usage vary depending on the monitoring objectives.

Many monitoring systems are based on recommendations for EPA compliance monitoring.[270] These include the U.S.-regulated criteria pollutants of PM (TSP, PM_{10}, and $PM_{2.5}$ mass), O_3, SO_2, NO_2, and CO. Meteorological data should also be monitored concurrently at air quality monitoring sites. In some areas, visibility and acid deposition may be important. Several different methods can be applied for these measurements that vary in the complexity, reliability, and detail of data. These range from simple passive sampling techniques to highly sophisticated continuous analyzers and remote sensors. Assessing which measurement technique is the most appropriate depends on the objective for which the measurements are to be conducted, as well as the resources available to achieve this objective. Current state-of-the-art continuous analyzers and remote sensors are able to provide highly time-resolved data that can be used to understand pollution evolution and distribution. However, most of these instruments are expensive to purchase and maintain, and they require considerable technical support, which often is not available in developing countries.

The selection of monitoring locations also depends on network objectives. One primary reason for monitoring ambient air pollutants is to provide information for estimating their likely effects, particularly on environmental and human health; therefore, monitoring stations are often established in population centers. They can be next to busy roads, in city center locations, or at a location of particular concern, such as a school or hospital. Background and boundary monitoring stations are also established to determine pollutants transported into and out of megacities.

In many urban areas, individuals spend a considerable amount of time indoors, where concentrations of pollutants are often quite different from those experienced outdoors. Indoor air pollution can be generated by the penetration of outdoor air. It can also be generated by indoor sources, such as combustion processes for heating and cooking, and other daily activities, such as cleaning. Therefore, an integrated assessment of indoor and outdoor exposure will allow the most appropriate, effective, and equitable controls on exposure to be imposed.

Once air quality data have been generated, quality assurance and control procedures should be developed and followed to ensure that the measurements obtained meet the specified level of accuracy and precision, and that those which do not are removed through data validation.

Emission Inventories

The most direct way to confirm that specific emission-control technologies are working effectively is to measure changes in the rate at which pollutants are released from relevant sources. Continuous emission monitors for PM, SO_2, and NO_x have been used for on-site stack sampling of large stationary sources, but these are not practical for the millions of smaller and mobile sources in a typical megacity. Temporally and spatially averaged emission inventories are constructed for this purpose.

Emission inventories tabulate emission rates from individual sources and source categories for the pollutants of interest. Although emission inventories are an essential tool for managing and regulating pollution, large uncertainties in emission rates, temporal cycles, spatial distribution, and source identification often confound the development of cost-effective control strategies. Emission inventories apply an emission factor that represents the mass of emissions per unit of activity (e.g., grams of $PM_{2.5}$ per kg of fuel consumed) times an activity factor (e.g., kg of fuel sold over a time period). Emission factors and activity levels are highly uncertain for vehicle exhaust, one of the largest source categories in megacity inventories. It is essential to reduce these uncertainties to manage air quality more effectively.

EPA publishes national emission inventories for criteria pollutants and hazardous air pollutants. The Emission Factors and Inventory Group of the EPA maintains a national emission inventory that characterizes emissions of criteria and hazardous air pollutants. Although these contain data for U.S. megacities, similar products are not easily obtainable from other countries.

To estimate the accuracy of the emission inventory it is useful to have an independent check with an alternative method that might be based on receptor modeling source apportionment[271,272] using emission ratios, multivariate methods, inverse air quality modeling, and equilibrium models. Receptor models relate speciated emissions to speciated source profiles. To the degree that a source profile is not unique (and many are not) or some emission spp. may be disproportionately removed by chemical reaction, deposition, or adsorption, source/receptor analysis will have uncertainties. Receptor model source apportionment shows the importance of sources to the emission problem directly, even whether the results are somewhat uncertain. Frequently, source/receptor analysis can point to a source that may have been overlooked. The benefit of an unequivocal and easily communicated "top-down" approach has value beyond confirming a "bottom-up" emission inventory. Receptor model source apportionment has found large discrepancies between ambient measurements and emission inventories for transportation-related vehicle exhaust and road dust.[272,273]

Mobile Source Emissions. Mobile source emission models[274,275] include the time and emission factors for vehicles while parked and at idle, for the frequency of cold and warm starts, and for vehicles at various speeds in congested and noncongested driving. Emission factors are derived from laboratory measurements of evaporative and tailpipe emissions for simulated driving on a dynamometer. Vehicles selected for measurements come from different vehicle types, technologies, and ages. However, on-road vehicle emissions may vary by orders of magnitude from vehicle to vehicle even within the same type, technology, and age because of deterioration and breakage of the fuel delivery and emission control system. A limited number of vehicles can be tested in the laboratory, and the most poorly maintained are rarely volunteered to be tested; high-emitting vehicles are often underrepresented in the vehicle samples that have been tested in the laboratory.[276]

Remote sensing has been used to estimate on-road vehicle emissions, usually while vehicles are in light-acceleration driving. An advantage of this technique is its ability to measure large numbers of vehicles, although the emission measurements represent less than 1 sec of driving for each vehicle. The technique has been used to: 1) verify the reduction of emissions from installing catalysts on vehicles in Mexico City,[277] 2) evaluate the reduced emission deterioration in newer vehicles,[278] 3) serve as the basis for estimating fuel-based emission inventories,[279] and 4) estimate the distribution of on-road high-emitting vehicles in various vehicle fleets.[280] Lidar-based remote sensors can detect low levels of PM emissions.[281] Remote sensing cannot measure evaporative emissions, and high evaporative emitters have not been identified by this technique.

On-board diagnostic (OBD) systems automatically monitor and document problems that lead to increased emissions from individual vehicles in an on-board computer. OBD systems alert the motorist by turning on the malfunction indicator light to indicate that repair is needed. Motorist response to the "malfunction indicator light on" is being studied, especially for vehicles that are no longer under warranty, in which case the motorist would have to pay for diagnosis and repair. Newer OBDII systems,[282] installed on U.S. vehicles from 1996 onward, monitor evaporative emission control systems better than current vehicle emission inspection tests, and EPA is recommending that OBDII be used to inspect vehicles. The newest OBDIII systems link on-board diagnostics with wireless communication so that emission systems can be monitored at a central facility. OBDIII is currently being evaluated on high-mileage vehicle fleets, especially taxis, in Los Angeles and the San Francisco Bay Area.[283,284]

In roadway tunnel studies,[285] air quality monitors are deployed inside tunnels and along roadways to characterize integrated emissions from vehicle fleets with minimal interference from other sources and atmospheric transformation. Tunnel measurements have led to revisions of emission models,[286] determined the effect of reformulated gasoline on HC spp. emitted by vehicles,[287] and quantified carbonyl and PAH emissions.

Mobile laboratories are designed to measure multiple pollutants while following vehicles on the road.[288,289,289a] These systems draw a portion or all of the exhaust plume through a series of instruments for characterization. They are often used as chase vehicles to sample individual plumes from preceding vehicles. Measurements made in the laboratory dilute the exhaust before analysis and the excess air and time delay change particle size depending on sampling conditions.

Portable emission measurement systems are used on a vehicle to measure real-time emissions.[290] These operate on battery power and can be located in the trunk or back seat of a vehicle, with sampling from the exhaust pipe or the diluted plume beyond the exhaust pipe. A cooperative research program to examine commercially available portable emission measurement systems devices is being organized.[291]

Aircraft and Satellite Observations. In addition to ground-based measurement, aircraft and satellite observations are useful for verifying elements of emission inventories and the location and extent of air pollution. Advanced multispectral satellite sensors can quantify trace gas concentrations and sometimes relate them to sources. The Global Ozone Monitoring Experiment (GOME) onboard the European Space Agency's Second European Remote Sensing Satellite (ERS-2) provides continuous spectral measurements of nadir backscattered earth radiances and solar irradiances in the UV/visible wavelength range. GOME measures integrated column concentrations of SO_2, NO_2, and HCHO that are often emitted by fossil fuel combustion.[292–294] Satellite plume detection can track long-range transport of gases and particles[295–298] and help researchers understand how meteorological situations influence air pollution on local, regional, and global scales.[299,300]

The scanning imaging spectrometer for atmospheric chartography (SCIAMACHY) on the European Space Agency Envisat satellite detects tropospheric gases and particles from lower earth orbit. The smaller ground pixel size of SCIAMACHY (30 km × 60 km) is comparable to the size of megacities, offering the possibility of estimating total emissions from these large urban expanses to create and verify inventories. SCIAMACHY's high spatial resolution also creates a higher probability of finding cloud-free ground pixels. SCIAMACHY extends the spectroscopic range into the IR to provide column-concentrations measurements for O_2, O_3, SO_2, NO_2, N_2O, bromine oxide, H_2O, HCHO, CO, CO_2, CH_4, other gases, clouds, and PM.[301] Validation from aircraft measurements and model intercomparisons, together with new spectral interpretation algorithms,[296] will make satellite data a quantitative tool for air quality research and management.

Air Quality Standards

Ambient air quality standards define pollutant levels that should not be exceeded if public health is to be protected. These standards require definition and justification for acceptable levels, averaging times, allowable number of exceedances, sampling frequency, measurement method, and sampling locations. All of these components of an air quality standard affect the extent of emission control required for their attainment. Most air quality standards are established to prevent adverse human health effects for a particular pollutant. Since pollutant to health effect relationships are uncertain,[302] the form and level of ambient standards vary from country to country, and this variability will affect the levels of control applied in different megacities. Ambient standards should provide a management tool that can be used progressively to improve air quality while at the same time remaining a realistically attainable target. Standards are effective only when compliance is measured and enforced.

Air Quality Forecasting

Air quality forecasting[303–305] uses source and receptor models to estimate the severity of future pollution events. These forecasts are communicated to the public via mass media so they can make decisions about their daily activities. Most forecasts produce one- to three-day advance estimates of pollutant concentrations. In phenomenological forecasts, an expert familiar with past air quality and meteorological information recognizes patterns that are conducive to high pollution levels. This information is used subjectively, relying on past experience. Empirical models use artificial intelligence computer programs to recognize patterns and project them into the future. Chemical transport models coupled to detailed meteorological forecasts are also being employed for forecasting.

Air Quality Simulation Models

Air quality simulation models[306,307] combine and systematize knowledge of emissions, meteorology, and atmospheric chemistry to estimate ambient concentrations. These models can be used to explain past episodes, to evaluate the potential effects of different emission reduction strategies, or to make air quality forecasts. Air quality models in common use include:

- California/Carnegie Institute of Technology (CIT) Model,[308] which was developed and applied in the SoCab[182] and the MCMA.[309] This model uses the SAPRC99 photochemical transformation mechanism[310] or the CalTech Atmospheric Mechanism.[311]
- MODELS-3/CMAQ Model,[312] the U.S. EPA model, which has been widely adopted within the modeling community in the United States. It is able to run the CB-IV,[313] RADM2,[314] and SAPRC99 chemical mechanisms.
- CAMx Model,[315] based on the earlier Urban Airshed Model (UAM)[316–318] which has also been widely used in California and more recently in Houston, TX.
- Multiscale Coupled MM5/Chemistry Model/ Weather Research and Forecast with Chemistry Model (MCCM, WRF-Chem),[319] links the Fifth-Generation NCAR/Penn State Mesoscale (MM5) meteorological model[320] and atmospheric chemistry models. This work is being continued with the development of WRF-Chem, placing the RADM2 chemical mechanism in-line with the WRF model.

Advanced air quality models contain modules for inorganic and organic aerosols using modal and sectional representations for particle size. For inorganic aerosols, the ISORROPIA equilibrium module[321] is used by CMAQ and CAMx models. The CIT model includes the SCAPE2 models[322] and WRF-Chem uses the MADE equilibrium module.[323] Secondary organic aerosol models also differ for the CIT[311] and CAMx[324] models, while CMAQ and WRF-Chem models use the formulation of Schell et al.[325]

A Master Chemical Mechanism (MCM) is being constructed using a large set of kinetics and product data for the elementary reaction steps of the VOC oxidation process.[326,327] The process of aromatic HC oxidation is becoming better understood,[328–333] leading to MCM updates that have been evaluated against simulation chamber measurements.[296,334,335]

The MM5[336,337] and CALMET[338] meteorological models generate three-dimensional wind fields from basic physics and from observations. CALMET is best suited to areas without complex terrain and with dense meteorological measurement networks. For complex flows, for example, in mountainous terrain or coastal areas, CALMET can be used as a filter to merge the results of prognostic models such as MM5 or RAMS[339] with available observations or as an interface between prognostic and air quality models. Martilli et al.[340] proposed an improved parameterization for urban surfaces, which is especially important in megacities, to take into account radiation trapping and shadowing along with turbulence effects based on simplified building geometries. MM5 is now in its last major release and will be replaced by WRF-Chem.[341]

EMISSION CONTROL STRATEGIES

Molina et al.,[3] an online supplement to this review, provides a detailed summary of different control measures that have been applied and are being considered for the nine case study megacities. There is a wide range of ways in which the same strategies can be implemented, but they can be classified into three major categories: 1) technology-based regulatory mandates on processes, fuels, and emission treatment; 2) economic instruments such as incentives, emission taxes, and emission trading; and 3) policy adaptation such as land-use planning, infrastructure development, and transport management.

Regulatory controls include emission limits imposed on industry and vehicles. These usually are based on technological limitations such as Maximum Available Control Technology for new emitters or Best Available Retrofit Technology for existing sources. Lloyd and Cackette[342] note that regulated emission limits often spur technological development, especially with respect to vehicle emissions. Economic instruments apply the power of the market to encourage use of cleaner technology and fuels, and are often based on the "polluter pays" concept.

Infrastructure modification can be applied to mobile and stationary sources. Road works and land use planning can reduce emissions from mobile sources, such as the building of ring-roads around heavily congested and polluted areas and the development of public transport to reduce vehicle usage. Large stationary emission sources can be moved out of the urban area, as has been done in Los Angeles and Mexico City.[11] Policy instruments can be used to reduce exposure to pollutants, for example, by encouraging investment in industries or their relocation away from residential areas.

The most effective air quality management strategies use a combination of these approaches together with public outreach programs, and enforcement through persuasion and incentives, to produce an equitable and appropriate reduction in emissions.

Technology-Based Regulations

Administrative and legislative frameworks are needed to ensure adherence to regulatory emission controls. Monitoring, reporting and auditing programs for effective control of sources often require considerable technical, human, and financial resources. Legislation enabling effective penalties to discourage violation of emission limits is essential. Cost analysis ensures that appropriate measures are taken so that the costs of establishing, carrying out, and enforcing the regulations are not disproportionate to their benefit. Cost analysis can also help to choose among alternative emission reduction strategies or to determine when making a strategy more stringent is no longer beneficial.

A U.S. National Research Council (NRC)[342a] panel recommended that regulatory agencies target groups of pollutants coming from the same sources rather than focus on single pollutants. Since air pollutants are transported from state to state and across international borders without regard for political boundaries, the study recommends that future regulations need to reach beyond individual cities, counties, and states. For megacities, this should apply as well to sovereign nations. The NRC panel noted that regulations for new cars and light trucks have greatly reduced vehicle emissions, but less progress has been made in the United States in reducing emissions from older heavy-duty diesel trucks, nonroad vehicles, and faulty automobiles. Although regulations governing new power plants and large factories have led to substantial reductions in emissions, many older "grandfathered" plants remain large sources of pollution. The study recommended that more emphasis be placed on measurable results than on the process of creating implementation plans. Improved tracking of emissions is needed to accurately assess which populations are at the highest risk of health problems from pollution and also to better measure the success of pollution-control strategies.

Over the last 30 years there have been radical improvements to fuels and technologies, which have contributed to a reduction in air pollution. However, there are significant constraints on what improvements to fuels and technologies alone can deliver. In many megacities, reductions in per-vehicle emission levels have been offset by increases in the numbers of vehicles and greater use of the same vehicle. For this reason, motor vehicle emissions must be a major focus of regulation in every megacity. Fortunately, transportation technology is rapidly advancing, and megacities in developing countries may be in a position to leapfrog older technologies.

Hybrid Vehicles. California required that 2% of vehicle sales had to be zero-emission vehicles by 1998. It was believed that battery-powered electric vehicles would meet the need, but available batteries limited their range to barely 100 km, and the vehicles did not sell. However, electric vehicle research created the technology for using smaller batteries that could be continuously recharged by a small gasoline-powered generator. These hybrid gasoline-electric vehicles have been shown to be near-zero-emission vehicles, efficient, and popular. At low speeds, where internal combustion engines are least efficient and most polluting, the hybrid drives the wheels with an electric motor. At higher speeds, where an electric motor lacks sufficient power, a small internal combustion gasoline engine provides an assist. The engine can directly spin the wheels or spin a generator to provide electricity. The Toyota Prius, which uses both a gasoline engine and an electric motor for propulsion, averages 23.2 km per liter (88 miles per gallon)—about double the mileage of a comparable gasoline car. Within a decade, the gas-electric combination could be offered in every category of vehicle the automaker sells, from subcompacts to heavy-duty pickup trucks.[343] Although hybrid vehicle purchase costs are higher than a comparable nonhybrid, the additional cost is recovered over time from fuel-cost savings. However, an additional expense may occur, possibly when the hybrid is owned by the second or third owner, when the battery needs replacement. Currently batteries are warranteed for 100,000 miles, and the replacement cost should be on the order of replacing a transmission.

Toyota is marketing its hybrid vehicles to the Mexican government and is testing the Prius to learn how to adapt its performance to Mexico City's driving conditions.[344] The Chinese government is also imposing strict emission and fuel economy standards to encourage automakers to introduce hybrid vehicles in its urban areas.

Fuel Cell Vehicles. Hydrogen (H_2)-powered fuel cell vehicles reduce transportation pollution because the combustion of O_2 and H_2 creates only water vapor as an emission product. Although the H_2 may have been produced from a fossil fuel, the fossil fuel conversion process would most likely be at a central facility where emission controls are more easily applied, and at a lower cost than that of individual vehicle controls. H_2 can also be produced by electrolysis of water with energy from solar- or wind-powered generators, and this would provide substantial global CO_2 emission reductions in addition to the NO_x, VOC, and $PM_{2.5}$ reductions that affect urban and regional environments. One of 14 vehicles in Japan may use fuel cells by 2020. In the United States, the President's Hydrogen Fuel Initiative forecasts H_2 fuel cell vehicles will enter the commercial mass market in 2020.[345] However, DeCicco et al.[346] believe current market or regulatory forces are not sufficient to result in fuel cells supplanting conventional vehicles in the United States and that other technologies will be needed to address transportation energy and pollution problems over the next two decades. In addition to developing the vehicle itself, H_2-powered vehicles will need a new fuel infrastructure.

A fuel cell can convert H_2 into electric energy much more efficiently than internal combustion engines can convert gasoline into mechanical energy. However, a fossil fuel well-to-wheels analysis of the energy efficiency of fuel generation to energy delivered does not see H_2 fuel cell vehicles as a way to reduce CO_2 emissions in the next 20 years, especially compared with more technologically demonstrated options. Improving mainstream gasoline and diesel engines and transmissions, and expanding the use of hybrids, will better reduce CO_2 emissions until nonfossil means for generating H_2 become cost-effective.[347]

Hydrogen-Powered Internal-Combustion Engine and Hybrid Vehicles. While automakers are advancing fuel cell vehicle technologies, the SCAQMD is developing H_2 refueling technologies. This is viewed as a bridging technology that will provide an incentive to develop H_2 storage and fueling technologies. The H_2 internal combustion engine vehicle project will convert 35 Toyota Prius hybrids to run on H_2 instead of gasoline, as well as compare different fueling strategies and H_2 production methods. The SCAQMD is co-sharing the project cost with a number of industries. The Toyota Prius was selected for this demonstration project because of its advanced hybrid technology. H_2 will be provided for these vehicles through a variety of methods, but mostly through electrolysis, which uses electricity and water. If the electricity were from nuclear power, no CO_2 emissions would be created. If the electricity were generated from renewable power sources, for example, wind and solar, then there are no pollutant emissions. Whether this can ultimately be done cost-effectively is not yet known. Although use of renewables is currently an expensive strategy, the SCAQMD intends to demonstrate various electrolysis processes to advance the technology, improve competition, gain experience, and, therefore, reduce the costs to accelerate commercialization.[162]

Ultra-Low Sulfur Fuels. Ultra-low sulfur fuels ($S < 10$–15 ppmw) enable much better emission control technology and result in less pollution from existing vehicles. Ultra-low sulfur diesel fuel allows the use of diesel particulate filters and NO_x traps.[342,349] Greater benefits and cost-effectiveness are achieved by one major decrease in sulfur content than are obtained by incremental reductions over a period of years.[350] Human health and environmental benefits because of sulfur reduction exceed costs by a factor of 10.[351] However, the natural tendency of governments is to proceed in several steps because financing the required oil refinery upgrades is costly.

Alternative Fuels. LPG (a mixture of propane and butane) and CNG (methane) are replacing gasoline and diesel fuel in some megacities. Hong Kong converted its entire taxi fleet from diesel to CNG. Sao Paulo, Brazil, uses ethanol which has a higher O_2 content than gasoline. LPG and CNG reduce emissions when they replace low-grade liquid fuels in unsophisticated vehicles. The International Association for Natural Gas Vehicles shows that Euro III buses using low-sulfur diesel fuel with continuously regenerating particulate traps emit low PM, but emissions are still higher than those from CNG-fueled buses, even when the CNG buses have oxidation or three-way catalysts. Emissions of aldehydes and mutagenicity were less for the buses using CNG. Carcinogenic PAHs in CNG emissions were not detected.[352]

CNG fueling also mitigates against adulteration with a cheaper fuel. This was a factor in the replacement of diesel with CNG buses in Delhi, since the diesel fuel was frequently blended with less expensive, and much more polluting, kerosene sold for home cooking. Brazil uses more ethanol as automotive fuel than other countries because of a subsidy for ethanol produced from sugar cane. Although ethanol has no sulfur and low PM and PAH emissions, it results in higher ambient concentrations of alcohols and aldehydes.[353]

Economic Instruments

Regulations take a "command-and-control" approach to emission reductions. Market-based programs are an alternative to command-and-control regulations[354,355] that allow a broad mix of emission reduction options to be exercised among a group of emitters. These include emission trading and congestion pricing.

Emission Trading. Emission trading has been most widely applied to reducing U.S. utility SO_2 emissions and is gaining favor for global CO_2 trading. A group of sources emitting into an airshed may be able to reduce overall emissions more cost-effectively by applying stringent controls to a few facilities and less stringent controls to others. This is best accomplished by setting an emission cap for a region and allocating allowances to the sources within that region. The allowances can be sold by sources that emit less than their allowances to those that emit more. The price of each allowance will depend on the cost of control and the overall emission cap. A source that installs high-efficiency pollution controls has excess credits to sell that can offset the cost of control. In some cases, emission reduction targets may be best met by changing the process or by fuel switching. Successful emission trading includes the following requirements: 1) emissions are not a local health risk, 2) tradable emissions are measured accurately and measurements can be audited, and 3) administrative costs of operating the trading program are not excessive (in comparison to the cost of administering a command-and-control program).

There are two basic kinds of international markets for GHG emission trading. In a "formal" emission trading market (sometimes called "cap and trade"), an international agreement sets a cap on aggregate emissions for a period of time and allocates GHG emission allowances among the participating countries for that period. The national governments then allocate these allowances to businesses within their countries. Emitters must hold allowances to cover every unit they emit; they can control emissions, buy additional allowances if their abatement costs are high, or sell allowances if their abatement costs are low.

In an "informal" market, an international agreement sets aggregate and national caps on emissions but does not allocate formal allowances. Each country may meet its cap through contracts for "abatement services" obtained both within and outside its territory. Emitters seeking to invest in abatement services may do so in their home country, and they may also purchase "credits" for emission reductions generated in other countries, including those not subject to an overall emission cap.[356]

The SoCAB has established SO_2 and NO_x credits under its Regional Clean Air Incentives Market (RECLAIM) program, which replaces certain command-and-control regulations with market incentives for facilities that meet the inclusion criteria. RECLAIM included 335 facilities at the end of the 2000 compliance year. More than (U.S.)$650 million in RECLAIM Trading Credits (RTC) have been traded since the adoption of RECLAIM, of which more than $48 million occurred in 2002. The annual average prices for SO_2 and NO_x RECLAIM Trading

Credits during 2002 were below the backstop price of $15,000 per ton.[348]

Emission reduction credits may be pegged at less than one-to-one; the emissions traded are required to be more than the credit received. This further reduces emissions with every trade. Emission caps may decrease over time to take advantage of (or even force) improvements in emission reduction technology. Allowances may also be purchased by environmental advocates and those permanently retired, thereby effectively limiting the upper limit on overall emissions.

Congestion Pricing. Effective February 2003, London implemented a program that charges drivers each time they enter the central city, similar to the toll charged at major bridge crossings. A 22 km^2 area, 1.2% of greater London, is subject to the charge. This congestion zone was always crowded with traffic and is also surrounded by perimeter roads that serve as its boundaries. Charges for individual vehicle registrations can be paid weekly, monthly, or annually. The charge is enforced by fixed and mobile cameras that are linked to automatic license plate number recognition technology. If no record of the £5 charge is paid by midnight, an £80 penalty is assessed against the vehicle owner. Persistent evaders are booted or towed. Exemptions and discounts (average 6000 per day) are provided for military vehicles, emergency services, taxis and licensed minicabs, disabled persons, buses, some alternative-fuel vehicles, and some health service workers. There is also a 90% discount for residents of the congestion zone.

For the first six months, passenger vehicle traffic decreased by 20% while bus usage increased by 14% during the peak traffic hours. Bus delays because of traffic congestion decreased and bus speeds increased, as did bus reliability measured in waiting time. There is a concern about negative financial impact on the local retail sector and on wider economic activity.[357]

For congestion pricing to be successful, the public needs to support the program. Extended studies and communications between city officials and the public were made to achieve this in London. Revenues are used only to reduce congestion and to improve public roads and transportation. Payments can be adjusted whether congestion levels change, since the purpose of the congestion charge is to elicit a behavioral response from the motoring public.

The cost of congestion is estimated as the cost of the fuel wasted by driving in a less efficient way, and by the time lost, compared with free-flowing traffic. It is estimated that drivers wasted 21.6 billion L of fuel, or ~60 L per person per year, in the 75 areas studied by the Texas Transportation Institute.[358] Annually, 3.5 billion hours of extra travel time are caused by traffic congestion. The total cost of congestion has risen to nearly (U.S.)$70 billion a year, which is $4.5 billion more than for the previous year. Santos[359] provides a different approach that gives lower estimates of marginal congestion costs for different types of roads in the U.K.

Policy Implementation

Urban policy-making is a complicated process that is influenced more by political and sociological factors than by scientific knowledge. Good urban planning is needed to improve megacity air quality by encouraging people to live closer to where they work, developing cost-effective and convenient mass transit networks, creating economic activities outside of megacities to reduce migration incentives, and strategically locating industries. Owing to the limited terms of many politicians and the lack of public awareness of the benefits, much of this policy is left to chance rather than to careful planning.

BARRIERS TO AIR QUALITY MANAGEMENT

The nine case studies of air quality management in Molina et al.[3] show that institutional capacity for controlling pollution is closely linked to financial capacity. Environmental planning agencies find themselves with inadequate budgets to address statutory mandates. There are conflicting interests among different government institutions; interagency conflicts often need to be resolved through political means. Megacities usually have multiple municipal governments with no regional authority for pollution and transporation issues. In some countries, because of the relatively weak political standing given to environmental issues, it is difficult to address air pollution when other needs are more pressing. When environmental and economic development policies conflict, economic development has more influence. Independently funded metropolitan institutions are essential to implement effective, but sometimes unpopular, policies to manage air quality.

However, as the economic well-being of megacity inhabitants increases, so does their concern about their environment, including the air they breathe and often see. In the United States, especially in California, citizens have been vocal about their desire for clean air. The Hong Kong government has responded promptly to citizens' concerns when the air quality was deemed unacceptable. In Bogotá and Santiago, stakeholder participation provided support for measures adopted in the public interest. In Mexico City, however, citizens have shown a fatalistic attitude toward the pollution problem and have been reluctant to pressure the government for action, except in the early 1990s, when air quality was at its worst. While the transport sector and other interest groups have strong lobbies, consumers have not organized to demand an efficient, safe, and clean transportation service. In Cairo, as in many lower income megacities, most of the population is struggling to survive and air pollution is not a high priority concern. Although wealthier people in these cities are aware of and concerned about air pollution, they are also concerned that the infrastructure might not be able to handle this problem.

Many countries have come up with ideas for controlling air pollution, but they don't have the technical training to define and implement these ideas. They do not have sufficient information to establish emission standards, emission inventories, and monitoring networks. Monitoring and modeling capacities are weak and there is a lack of research on health effects. Although several international organizations can provide technical assistance, it is better if local groups convince their governments that there is an environmental pollution problem. In the long term, capacity building will be more effective to removing barriers than short-term technical help from outsiders.

SUMMARY AND FUTURE OUTLOOK

Although megacities are defined as those with more than 10 million inhabitants, there are more than 100 cities worldwide that contain the same types of problems, and could even be classified as megacities. These are contiguous urban areas that are magnets to growth owing to the concentration of economic activity, services, and opportunity. Urban areas are growing faster than nonurban areas, and higher levels of pollution accompany this growth. However, owing to their dense populations, increasing wealth, and central governments, megacities can implement policies that can minimize environmental degradation, including air pollution.

Air pollution adversely affects human health through the cardiovascular and respiratory systems. Health studies throughout the world have reached similar conclusions: PM, O_3, and other air pollutants attack the cardiovascular and respiratory systems and are associated with premature mortality as well as sickness. SO_2 and NO_x are the main precursors of acid rain pollution that can harm forests, lakes, and river ecosystems, and also have been blamed for damaging buildings and statues in cities. SO_2 and NO_x can be generated hundreds of kilometers away from the areas affected by acid rain. Agricultural practices such as "slash and burn" generate smoke and precursors of photochemical smog. These emissions added to the outflow from urban centers lead to the degradation of air quality on regional scales and also potentially affect climate.

Reducing sulfur in fuel and after-combustion exhaust treatments are strategies that have minimized sulfur air pollution in practically all cities of the developed world, as well as in many urban centers of the developing world. Much has also been learned about reducing emissions of photochemical smog precursors—NO_x and VOCs—from motor vehicles and industrial activities. Efficient clean technologies have led to new car emissions of smog precursors 50–100 times smaller than those from older cars without emission controls. However, appropriate maintenance of cars with emission controls, even the newest cars, is an important issue because when controls fail emissions increase. Vehicle maintenance is expensive and establishing regulations and enforcing them for large numbers of vehicles is difficult, particularly in places where the population has limited economic resources. Fine particulate matter and hazardous VOCs are emitted from diesel vehicles, especially those that are old and not well maintained. New emission control technologies have recently been developed to reduce particulate matter from diesel vehicles, although these technologies require ultra-low sulfur diesel fuel, which is more expensive to produce. New urban buses designed to use natural gas have low PM emissions, but may emit high levels of unburned or partially burned fuel. Conversions of existing vehicles to use natural gas or LPG must be done correctly if low emissions are to be achieved.

A variety of measures have been applied to reduce motor vehicle emissions besides engine improvement and exhaust controls. Some of these measures are also aimed at reducing traffic congestion, which in turn exacerbates emissions. Further, people using congested roads or living nearby have increased exposure to air pollutants. One way to reduce congestion is by limiting the circulation of vehicles. London has started doing this by charging vehicles to enter part of the city. Another example is the "no drive day" program, which may have unintended consequences if not properly designed. In the Mexico City area, it appears to have induced the purchase of a second vehicle, often older and more polluting. A more effective strategy, restricting the circulation of the vehicles only during peak hours, is being implemented in Bogotá, Santiago, and São Paulo.

Given the expected scale of urban population growth in the coming decades, continued growth in the number of vehicles will pose an enormous challenge in managing megacities, especially in the developing nations. Effective strategies to control vehicle growth and traffic intensity in some cities can be adopted in others facing similar challenges.

Scientific Knowledge

Air pollution science has progressed steadily in the past decades because of improvements in the ability to measure pollutants, precursors, and reactive intermediates.

This information has facilitated the development of improved computer models of the complex photochemistry that cause the formation of ozone, other oxidants and secondary particulate matter. These scientific advances motivate further research to gain a better understanding of how air pollution is formed in megacities and how best to control it.

The MCMA 2003 field measurement campaign demonstrated that it is now possible to measure in real time, that is, on a time scale of seconds, the gas-phase concentrations of a variety of key intermediates in the formation of photochemical smog, as well as the size-resolved composition of suspended particles. Such highly time-resolved data allowed close correlation of photochemical pollutant precursors, intermediates and products and will lend a better understanding of closely coupled photochemical processes. On the other hand, much remains to be learned about the complex chemical processes that characterize the atmospheric oxidation of all but the simplest hydrocarbons. Laboratory research and quantum chemical calculations need to be conducted to further elucidate these gas-phase oxidation mechanisms at a molecular level.

In addition, there is a need to better elucidate the processes that lead to the formation, chemical evolution, growth and removal of atmospheric particles—in particular those containing organic spp. because of their importance for human health and climate change. Although it is well established that atmospheric particulate matter—PM_{10} and $PM_{2.5}$—have strong impacts on human health, an important gap exists in our knowledge of the chemical identity of the particles that actually do the damage. Organic chemicals such as PAHs adsorbed on soot, as well as some heavy metals contained in fine particles, are possible culprits, although it is likely that a variety of compounds are hazardous. Further developments in laboratory and field instruments for real-time particle characterization will pay large scientific dividends. It is also not known what role physical parameters, including particle size, surface area, or particle mass play in degrading human health. Advances in health studies will require a close collaboration between epidemiologists, physiologists and atmospheric scientists.

However, we should stress that enough is known already to amply justify emission control measures aimed at reducing ambient levels of criteria air pollutants that exceed current standards. In many cities of the developing world the concentrations of many criteria pollutants are not routinely measured, even when the concentrations are known or suspected to be high. Thus, there is a pressing need to start monitoring air pollutant levels routinely in such cities.

Field measurement campaigns focused on the characterization of the outflow of air pollutants from megacities need to be carried out to assess their regional and global impacts. There is also a clear need to establish long-term measurement programs to characterize air quality on a regional to global scale. Such measurements are challenging: the relatively short atmospheric residence times of spp. such as ozone, NO_x and aerosols (days to months) require frequent measurements and good spatial coverage, in contrast to long-lived spp. such as CO_2 and chlorofluorocarbons, whose global concentration can be characterized with less than a dozen properly located monitoring stations. A better understanding of the potential climate effects of atmospheric particles, particularly those containing black carbon or soot, is also required.

Interdisciplinary Research

To address the pressing environmental problems confronting megacities, it is essential to bring together world-class national and international experts in science, engineering, economics, and other social and political sciences to engage in collaborative research that leads to both holistic assessments of the complex environmental problems and the development of practical solutions. This will necessarily involve face to-face interactions among all relevant stakeholders, including the civic leaders responsible for protecting the health of megacity populations. Cost-effective solutions to such complex problems can only be developed through consensus building.

The methodology adopted must be multidisciplinary, taking into account political, scientific, technical, social and economic aspects. The social, economic and political barriers characteristic of the megacity problem will need to be recognized and analyzed. A strategy to overcome these barriers—which might include advocacy, public pressure, education, etc.—will have to be developed jointly with the relevant stakeholders. Furthermore, various research activities, financial analysis, coordination and communication among government officials, stakeholders, and experts in the academic and industrial sectors will all be required to successfully develop and implement air quality improvement plans.

Institutional Improvement

Most urban environmental problems can only be successfully solved by establishing a strong regional authority committed to reducing pollution. Furthermore, substantial progress requires good communication with the public. Successful examples of this approach are found in Los Angeles and Bogotá. Deficiencies in air quality management are also exacerbated by a lapse in integrating relevant metropolitan policies for transportation, land use and air quality, and lack of connection with policies affecting population, energy supply, and other key urban factors. Strong political will is essential to develop institutional capacity, ensure that funding is available and properly allocated, and to increase local, state, and federal coordination.

Air pollution is transported from state to state and across international borders. Therefore, air quality management agencies should be given greater statutory responsibility and authority to deal with these problems in a regional context, and international coordination and collaboration should be strongly encouraged.

Regulation and Enforcement

An important outcome of the megacity case studies is the importance of enforcement of emission control strategies. Enabling legislation is important, but enforcement is also necessary. If reducing air pollution is not a priority for a megacity, it will almost surely become a worsening problem. Many developing countries have extensive regulations on pollution which, however, all too often are not applied effectively because of the lack of proper institutions, legal systems, political will, and competent governance. Unfortunately, established political and administrative institutions are usually obsolete for dealing with the problems that occur with the expansion of megacities, particularly where economic and social change is rapid. Political leadership is needed to cut through overlapping and conflicting jurisdictions and short-time horizons. Experiences in some cities (like Bogotá and Santiago) show that radical and integrated packages of transport measures, based upon management of road space and an enhanced role for high quality bus and rapid transport systems can deliver efficiency and equity and be economically, environmentally and socially sustainable. But this is not possible without strong political leadership.

Stakeholder Involvement

Over the past few decades, there have been significant political changes with profound implications for urban areas and for the urban and global environment. There is increased pressure from the citizens for participation, accountability and transparency in government. Efforts to improve urban governance involve activities such as promoting participatory processes and developing effective partnerships with and among all stakeholders of civil society, particularly the private and community sectors. Public participation adds legitimacy to these policies and helps to bring about their success. Many policies will not work unless stakeholders have ownership and share responsibility for their implementation. Stakeholder 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. In this way, the accountability of public officials and institutions can be greatly improved and long-term continuity is facilitated, in spite of frequent personnel changes in government agencies.

Capacity Building

Some of the common obstacles in the air quality management in many megacities, especially of the developing nations, include insufficient understanding of the connection between the underlying scientific, economic, and social issues, and difficulty in comprehensively addressing the problem with limited personnel, resources, and infrastructure. There is a clear need to increase the number of professionals—in government, industry, and academic institutions—with a basic understanding of the different aspects of environmental problems.

Sustainable Transportation

There is a strong linkage between air quality and the transportation sector. First, transportation emissions are the major cause of air quality problems in many large urban centers, and the trend in the megacities of the developing world is for these emissions to become the dominant source of air pollutants. Second, economic growth is closely linked to personal and freight transportation and efficient mobility, so restrictions to transportation activities, while perhaps improving air quality, could hinder economic growth. On the other hand, without any traffic control or infrastructure improvement the increasing number of vehicles will cause congestion resulting in both poor air quality and hindered economic growth.

The challenge is thus to improve air quality while ensuring personal and freight mobility. It is clear that no single strategy will suffice to achieve this difficult goal. Rather, what is required is a set of integrated strategic options involving cleaner fuels, advanced vehicle technologies, institutional change, infrastructure investment, operations improvements, and active stakeholder participation. Quantitative analyses of transportation strategies involving multi- and inter-modal networks need to be carried out, taking into account both personal mobility and freight transportation needs.

Reduction in per-vehicle emission levels resulting from new, clean technologies is often largely offset by increases in the numbers of vehicles in many large urban centers. This growth in the size of the vehicle fleet has in turn generated serious congestion and air quality problems. Growth in vehicle ownership needs to be decoupled from daily vehicle usage, an approach that requires the availability of very efficient public transportation. Historically rapid urban public transport systems were built underground or on dedicated rail lines. A much less expensive alternative is to use surface streets and BRT systems, such as the one developed in Bogotá, where prime road space was allocated to low emission buses, resulting in reduced travel duration, improved air quality, and increased pedestrian space and bike use, while decreasing private vehicle use. Santiago de Chile has also initiated a BRT and integrated bus-metro system, reversible street directions, and land-use planning structure to significantly reduce trip duration. A BRT system is also under development in the Mexico City metropolitan area, which already has an extensive metro system.

Clean Vehicle and Fuel Technology

In terms of mobile source emissions, new vehicle technology has been responsible for enormous improvements in new vehicle emissions performance. In California, 40 years of such improvements have resulted in a slow but consistent reduction in air pollution despite the huge increase in the numbers of vehicles and vehicle miles traveled. The use of clean vehicle technologies in developing countries is occurring because vehicle emissions controls are being applied worldwide, as gasoline fuel quality has been improved through removal of lead. The next generation of new gasoline vehicle emissions control technology will depend on reducing sulfur to very low levels. Emissions from diesel trucks, motorcycles, and two-stroke engines have not progressed as rapidly. Issues such as fuel contamination and limited financial resources make dealing with pollution from these vehicles difficult. Progress is being made in some countries by fuel switching to CNG and removing two-stroke engines.

Improved Inspection and Maintenance Program

Fitting vehicles with advanced emission control technologies is not sufficient; appropriate maintenance is essential. Further, old vehicles remain in the fleet because the cost of replacement is often perceived as being too high for populations in the developing world, because the consequent public health costs are not taken into account. In fact, these countries frequently use the cast off vehicles that people in the developing world no longer want, often because the vehicle is polluting too much. This problem is particularly difficult to solve with heavy-duty vehicles, because the existing fleet is likely to remain functional for decades and cannot be ignored. Heavy-duty vehicle emissions standards are evolving, and one of the technologies of growing interest is the retrofit of oxidation catalysts with particulate traps for diesel engines. In Hong Kong, for example, 40,000 diesel vehicles were successfully retrofit with oxidation catalysts.

Appropriate maintenance and a good emissions inspection and maintenance program may be difficult to implement, and yet the alternative is more expensive. There are several requirements for a successful inspection and maintenance program: very strict enforcement, public awareness, good inspector training, and separation of testing and repair. Government enforcement and auditing is also very important.

CONCLUSIONS

Much progress has been made in combating air pollution problems in developed and some developing world megacities. However, there continue to be many areas where comprehensive solutions appear to be elusive. By learning from the experiences in other regions, government officials may be able to overcome problems that appear insurmountable. There is no single strategy for addressing air pollution problems in megacities. A mix of policy measures best suited for each city's challenges and customs will be needed to improve air quality. An important lesson learned throughout the world is that addressing air quality issues effectively requires a holistic approach: one that takes into account scientific, technical, existing infrastructure, economic, social, and political factors. A successful result will be to arrive at integrated control strategies that are effectively implemented and embraced by the public.

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