2004 Critical Review Summary

Megacities and Atmospheric Pollution

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INTRODUCTION

During the next three decades, the world population is expected to increase from 6.1 billion to 8.1 billion, with nearly all of this growth concentrated in urban areas (from 2.9 billion to 4.9 billion). While only 30% of the world population lived in urban areas in 1950, this has increased to 47% by 2000 and is expected to reach 60% by 2030, of which 80% (3.9 million) will be living in less developed regions.

The number, size and geographical distribution of large urban centers have increased dramatically during the second half of the 20th 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 20th century; today, there are about 300. 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. In 1900, 9 of the 10 largest cities were in North America and Europe, whereas today only 2 are in the developed world. In 1950, New York and Tokyo were the only megacities. That number grew to 4 by 1975 and to 20 by 2000. Figure 1 shows the locations of the 20 megacities around the world.

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 (GNP). 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, and international migration is another factor. But the largest contributor to urban growth is the increasing number of people, especially in the developing world.

Growth in large cities is often accompanied by increases in urban poverty. 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).

High concentrations of people and their activities are exerting increasing pressure on the natural environment with consequences at urban, regional, and global levels. 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.

Although megacities are often defined as urban agglomerations 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 for growth owing to the concentration of economic activity, services, and opportunity. Urban areas are growing faster than non-urban areas, and higher levels of pollution accompany this growth. However, owing to their dense populations, increasing wealth, and central governments, megacities are capable of implementing policies that can minimize environmental degradation, including air pollution.

SCOPE OF REVIEW

The 2004 Critical Review[1] and on-line supplment[2] address 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.

In this review, the driving forces behind the formation and growth of megacities and their consequences are described. The nature of megacities, their air quality problems, and the associated science are briefly addressed. Impacts of emissions and the ambient concentration of pollutants in megacities on the health of their populations, visibility (urban and regional haze), ecosystems (including acid and fixed nitrogen deposition, photochemical oxidant damage, and photosynthetically active radiation), climate change, and global pollutant transport are evaluated in the review. The review summarizes air quality management tools available for large urban centers and their air quality outlook.

Nine urban centers are examined in this review as case studies: 1) Los Angeles, USA; 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. Table 1 summarizes selected statistics for the nine case study cities. These cities range from urban areas with relatively clean air in industrialized nations to highly polluted cities in the developing world. The review describes air quality in these nine urban centers 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.

The Critical Review supplement[2] details the air quality management capabilities and strategies of the nine case study cities and some of the barriers to implementing air quality management programs. Similar strategies can be implemented in many different ways, but they belong to 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.

AIR QUALITY CONSEQUENCES OF MEGACITIES

Urbanization and industrialization have important consequences for the Earth's atmosphere. 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, which may be using adulterated fuels. 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. Long-range transport of ozone (O_3) and particulate matter (PM) influences air quality and climate in regions far from megacity sources.

Cities create heat islands that aggravate pollution, alter regional meteorological conditions, and even global chemistry and climate. Higher ambient temperatures enhance O_3 and some secondary PM formation. Warmer temperatures in the summer increase the demand for cooling and electricity, leading to yet higher temperatures in the city.

Air pollution adversely affects human health through the cardiovascular and respiratory systems and is associated with premature mortality as well as sickness. Sulfur dioxide (SO_2) and nitrogen oxides (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. Agricultural practices such as "slash and burn" generate PM and gaseous precursors of photochemical smog. These emissions, added to the outflow from urban centers, degrade air quality on regional scales and also affect climate.

Much of the air pollution in the cities of developed countries is generated by motor vehicles, since stringent controls limit emissions from many large industrial sources. In developing countries, rapid industrialization is often combined with increases in both human population and motorization.

EMISSION REDUCTION STRATEGIES

A variety of measures besides engine improvement and exhaust controls on new vehicles have been applied to reduce motor vehicle emissions. Some of these measures reduce traffic congestion, since congestion exacerbates emissions. People using congested roads or living near them have increased exposure to air pollutants. One way to reduce congestion is by limiting the circulation of vehicles. London charges a fee when vehicles enter a designated part of the city. "No drive day" programs may have unintended consequences if not properly designed. In Mexico City, such a program appears to have induced the purchase of a second vehicle, often older and more polluting. A more effective strategy that restricts the circulation of vehicles only during peak hours is being implemented in Bogotá, Santiago and São Paulo.

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 volatile organic compounds (VOCs)—from motor vehicles and industrial activities. Efficient, clean technologies have reduced new vehicle emissions of O_3 and PM precursors 50 to 100 times compared to older cars without emission controls. However, appropriate maintenance of vehicles with emission controls, even the newest ones, is important because emissions increase when controls fail. Vehicle maintenance is expensive, and establishing regulations and enforcing them for large numbers of vehicles is difficult in places where the population has limited economic resources.

Fine PM and hazardous VOCs are emitted from diesel vehicles, especially those that are old and not well maintained. New emission control technologies can reduce PM from diesel vehicles, although these technologies require ultra-low sulfur diesel fuel that is costly to produce. New urban buses designed to use natural gas have low PM emissions, but they may emit high levels of unburned or partially burned fuel. Conversions of existing vehicles to use natural gas or liquefied petroleum gas (LPG) must be done correctly if low emissions are to be achieved.

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 recent decades due to 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 forms O_3, other oxidants, and secondary PM. 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 intensive field measurement campaign conducted in the Mexico City metropolitan area in 2003 by an MIT-led multi-national team of atmospheric scientists demonstrated that it is now possible to continuously measure gas-phase concentrations of key intermediates in O_3 formation along with the size-resolved composition of PM. Such highly time-resolved data allows close correlation among the photochemical pollutant precursors, intermediates, and products. It also facilitates an understanding of closely coupled photochemical processes. Nevertheless, much remains to be learned about the complex chemical processes that characterize the atmospheric oxidation of all but the simplest hydrocarbons (HC). Laboratory research and quantum chemical calculations would further elucidate these gas-phase oxidation mechanisms at a molecular level.

There is a need to better explain the processes of formation, chemical evolution, growth, and removal of atmospheric particles—especially those containing organic species, because of their impacts on human health and climate. Although it is well established that atmospheric PM —PM_{10} and $PM_{2.5}$—have strong impacts on human health, research needs to be conducted to explain the chemical identity of the particles that actually do the damage. Organic chemicals such as polycyclic aromatic hydrocarbons (PAHs) adsorbed on soot, as well as some heavy metals contained in $PM_{2.5}$ 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. The role that physical parameters—including particle size, surface area, and particle mass—play in degrading human health needs to be understood. Advances in health studies will require a close collaboration between epidemiologists, physiologists, and atmospheric scientists.

Even though uncertainties exist, enough is known already to justify emission control measures that reduce ambient levels of criteria air pollutants that exceed current standards. In many cities of the developing world, concentrations of many criteria pollutants are not routinely measured, even when the concentrations are known or suspected to be high. 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. Long-term measurement programs are needed to characterize air quality on regional and global scales. Such measurements are challenging: the relatively short atmospheric residence times of species such as O_3, NO_x, and PM (days to months) require frequent measurements and dense spatial coverage, in contrast to long-lived species such as carbon dioxide (CO_2) and chlorofluorocarbons (CFCs), whose global concentration can be characterized with fewer 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

National and international experts in science, engineering, economics, and other social and political sciences must engage in collaborative research that leads to holistic assessments of complex environmental problems and the development of practical solutions. Face-to-face interactions are needed among relevant stakeholders, including civic leaders responsible for protecting the health of megacity populations. Cost-effective solutions to such complex problems can be developed only through consensus building.

The methodology adopted must take into account political, scientific, technical, social, and economic aspects. The social, economic, and political barriers characteristic of megacity problems will need to be recognized and analyzed. A strategy to overcome these barriers —which might include advocacy, public pressure, education, etc.— must be developed jointly with the relevant stakeholders. Research activities, financial analyses, and coordination and communication among government officials, stakeholders, and experts in the academic and industrial sectors are needed to successfully develop and implement air quality improvement plans.

INSTITUTIONAL IMPROVEMENT

Most urban environmental problems can be successfully solved only by establishing a strong regional authority committed to reducing pollution. Progress requires good communication with the public. Successful examples of this approach are found in Los Angeles and Bogotá. Air quality management is impaired by a lack of integration among policies for transportation, land use, and air quality. 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.

An important outcome of the megacity case studies is the importance of enforcement of emission control strategies. If reducing air pollution is not a priority for a megacity, air quality will worsen. Many developing countries have extensive regulations on pollution that are not effective because of the lack of proper institutions, legal systems, political will, and competent governance.

Established political and administrative institutions are usually too obsolete to deal 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 (such as 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. Air pollution is transported from state to state and across international borders. Therefore, air quality management agencies need greater statutory responsibility and authority to deal with these problems in a regional context. International coordination and collaboration should be strongly encouraged.

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 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. Long-term continuity is facilitated in spite of frequent personnel changes in government agencies.

Many countries do not have sufficient information to establish emission standards, emission inventories, and monitoring networks; there is also 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.

SUSTAINABLE TRANSPORTATION

Economic growth is closely linked to personal and freight transportation and efficient mobility. Restrictions to transportation activities, while improving air quality, could hinder economic growth. However, without any traffic control or infrastructure improvement, increasing numbers of vehicles will cause congestion resulting in both poor air quality and hindered economic growth. The challenge is to improve air quality while ensuring personal and freight mobility. What is required is a set of integrated strategic options involving cleaner fuels, advanced vehicle technologies, institutional change, infrastructure investment, operational improvements, and active stakeholder participation. Quantitative analysis 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 vehicle use in many large urban centers. Growth in vehicle ownership needs to be decoupled from daily vehicle usage, an approach that requires the availability of 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 bus rapid transit (BRT) systems, such as the one developed in Bogotá, where prime road space was allocated to low emission buses. Reduced travel duration, improved air quality, increased pedestrian space and bike use, and less private vehicle use were the results. Santiago de Chile has also initiated a BRT and integrated bus-metro system, reversible street directions, and land-use planning to reduce trip duration. A BRT system is also under development in the Mexico City metropolitan area, which already has an extensive metro system.

In California, 40 years of vehicle technology improvements have resulted in a slow but consistent reduction in air pollution despite an increase in vehicle kilometers traveled. The use of clean vehicle technologies in developing countries is occurring because vehicle emissions controls are being applied world-wide, as gasoline fuel quality has been improved through removal of lead. The next generation of control technology depends on reducing sulfur to very low levels. Emission reduction from diesel trucks, motorcycles, and two-stroke engines has not progressed as rapidly as for passenger cars. Progress is being made in some countries by fuel switching to compressed natural gas (CNG) and replacing two-stroke with four-stroke engines.

Appropriate maintenance is essential. Old vehicles remain in the fleet because the cost of replacement is often perceived as being too high for many in the developing world, but the consequent public health costs are not taken into account. These countries frequently use cast off vehicles from the developed world. This problem is particularly difficult to solve with heavy-duty vehicles, because the existing fleet is likely to remain functional for decades. 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.

However, appropriate maintenance and a good emissions inspection and maintenance (I/M) program may be difficult to successfully implement. Requirements for a successful I/M program include strict enforcement, public awareness, inspector training, and separation of testing and repair. Test station auditing and evaluating the effect of the program are also important.

CONCLUSION

Megacities present a major challenge for the global environment. However, as the centers of economic growth, technological advances, social dynamics, and cultural production, these urban areas also offer opportunities to manage a growing population in a sustainable way. Well-planned, densely populated settlements can reduce the need for land conversion and provide proximity to infrastructure and services. Sustainable development must include: 1) appropriate air quality management plans that include 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.

Much progress has been made in reducing air pollution in developed and some developing world megacities. However, there are many areas where comprehensive solutions are elusive. By learning from the experiences of 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.

REFERENCES

1. Molina, M.J.; Molina, L.T. 2004 *Critical Review: Megacities and Atmospheric Pollution.* J. Air Waste Manage. Assoc. Molina, M.J., Molina, L.T., Megacities and Atmospheric Pollution, J. Air & Waste Manage. Assoc., 54, 6, 644-680 (2004).

2. Molina, L.T., M.J. Molina, R.S. Slott, C.E. Kolb, P.K. Gbor, F. Meng, R.B. Singh, O. Galvez, J.J. Sloan, W.P. Anderson, X.Y. Tang, M. Hu, S. Xie, M. Shao, T. Zhu, Y.H. Zhang, B.R. Gurjar, P.E. Artaxo, P. Oyola, E. Gramsch, D. Hidalgo and A.W. Gertler. *2004 Critical Review Online Version: Air Quality in Selected Megacities*, http://www.awma.org (2004).