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What is Particulate Matter?

Composition & Science

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PM?

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What is Particulate Matter – Composition & Science?

For urban air pollution, among the many pollutants that are critical, the particulate (PM) pollution is the most important[1]. The issue of urban air quality is receiving increasing attention as a growing share of the world's population is now living in urban areas[2]. The urban sector of the world's population is already 50 percent and it is expected to reach ~75 percent by 2030. Growing levels of urbanization in developing countries have generally resulted in increasing air pollution due to higher activity in the transportation, energy demand among industrial sectors, and lagging air pollution control programs. Unfortunately, air pollution from fuel combustion and industrial activity has important detrimental impacts on human health and the environment. For example, the health impacts, The World Health Organization (WHO)[3] estimated that urban air pollution from particulate matter (PM) accounts for ~800,000 deaths annually and the burden occurs primarily in developing countries[4].

This review on PM arises from a concern over the lack of comprehensive information on the sources, science, and composition. Without understanding the sources of pollution and their strengths, it is difficult for policymakers to formulate rational, effective policies and make informed investment decisions related to air quality improvements[5].

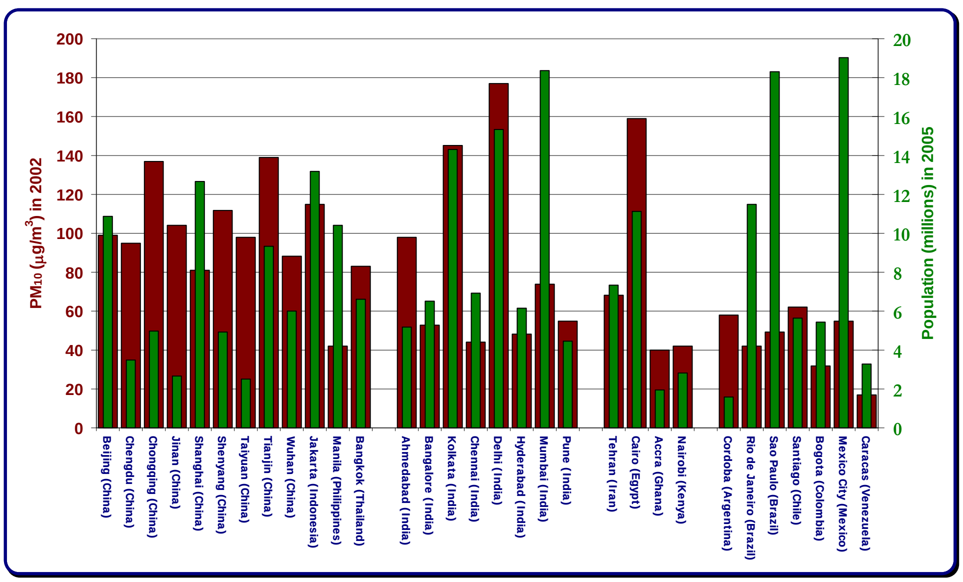

Figure 1: Population vs. PM_{10} in urban centers (WDI, 2007)[6]

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[1] Molina, M. J. and Molina, L. T. 2004. Megacities and atmospheric pollution. J. Air Waste Management Assoc. 54(6):644-680.

[2] World is Soon Half Urban (May, 2008) - http://www.worldwatch.org/node/5455

[3] WHO challenges world to improve air quality – www.who.int/mediacentre/news/releases/2006/pr52/en

[4] Comparative Quantification of Health Risks - http://www.who.int/publications/cra/en/

[5] SIM Series 2008-003 "Informed Decision Support for AQM in Developing Cities" @ http://www.urbanemissions.info/simair

[6] World Development Indicators - http://devdata.worldbank.org/data-query/

What is Particulate Matter?

Particles suspended in the air are classified by size (aerodynamic diameter) and chemical composition, and are often referred to as PM or aerosols. Airborne particles are classified by size into coarse, fine, and ultrafine particles (**Figure 2**).

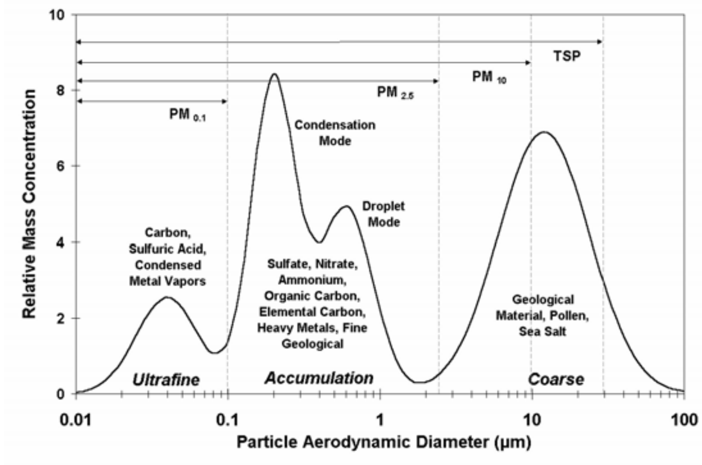

Figure 2: Particulate Size Distribution[7]

PM is generally measured in terms of the mass concentration of particles within certain size classes:

- Total suspended particulates (TSP, with aerodynamic diameter <~30 microns (µm)
- PM_{10} (with an aerodynamic diameter of less than 10 µm, also referred to as **coarse**)
- $PM_{2.5}$ (with an aerodynamic diameter of less than 2.5 µm, also referred to as **fine**)
- Ultrafine PM are those with a diameter of less than 0.1 micron

These size distinctions result because coarse and fine particles come from different sources or formation mechanisms, which lead to variation in composition and properties. The range of sizes also affects the atmospheric lifetime, spatial distribution, indoor-outdoor ratios, temporal variability, and health impacts of particles.

It is not possible to define a universal composition of fine and coarse particle portions that applies to all times and places. Some of these particles occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray and some exist as a result of human activities, such as fossil fuel combustion, industrial emissions, and land use change.

In terms of mechanisms of emissions, PM is classified into two categories, primary and secondary particles.

- Primary particles are emitted directly into the atmosphere from sources such as burning, industrial activities, road traffic, road dust, sea spray, and windblown soil and are composed of carbon and organic compounds, metals and metal oxides, and ions.

[7] Dr. Judith Chow, Desert Research Institute, Reno, NV, USA

- Secondary particles are formed through the chemical transformation of gaseous. Gaseous pollutants such as Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x), certain Volatile Organic Compounds (VOC's), and Ammonia (NH_3) among others, into Sulfates, Nitrates, Secondary Organic Aerosols, and Ammonium Ions.

The secondary particles are most often part of the fine PM fraction.

The life time of the particles also varies because of the size and shape of the particles. The coarse particles have an average life time (resuspension before they settle on a canopy or wet deposited due to precipitation) between minutes to hours, while the fine particles average between days to weeks. Also, the travel distances for coarse particles range from 1 to 10s of kilometers and the fine particles average from 100s to 1000s of kilometers. Although, during the dust storms (from Asia and Saharan Africa), the coarse PM is known to travel long distances.

What makes PM – Composition?

While some countries are still monitoring for TSP, a growing number of urban centers are focusing on finer fractions, e.g. PM_{10}, $PM_{2.5}$, and sub-micron PM. [8]Six major components account for nearly all of the PM mass in most urban areas:

1. Geological material (oxides of Al, Si, Ca, Ti, and Fe)
2. Organic matter/carbon (OC- consisting of hundreds of different compounds)
3. Elemental carbon (EC) (also termed black carbon or soot)
4. Sulfates
5. Nitrates
6. Ammonium.

Table 1: Marker Elements Associated with Various Emission Sources

Emission Source	Marker Elements*
Soil	Al, Si, Sc, Ti, Fe, Sm, Ca
Road dust	Ca, Al, Sc, Si, Ti, Fe, Sm
Sea salt	Na, Cl, Na^+, Cl^-, Br, I, Mg, Mg^{2+}
Oil burning	V, Ni, Mn, Fe, Cr, As, S, SO_4^{2-}
Coal burning	Al, Sc, Se, Co, As, Ti, Th, S
Iron and steel industries	Mn, Cr, Fe, Zn, W, Rb
Non- Ferrous metal industries	Zn, Cu, As, Sb, Pb, Al
Glass industry	Sb, As, Pb
Cement industry	Ca
Refuse incineration	K, Zn, Pb, Sb
Biomass burning	K, C_{ele}, C_{org}, Br, Zn
Automobile gasoline	C_{ele}, Br, Ce, La, Pt, SO_4^{2-}, NO_3^-
Automobile diesel	C_{org}, C_{ele}, S, SO_4^{2-}, NO_3^-
Secondary aerosols	SO_4^{2-}, NO_3^-, NH_4^+

** Marker elements are arranged by priority order*

[8] Chow, J.C. (1995). "Critical Review: Measurement Methods to Determine Compliance of Ambient Air Quality Standards for Suspended Particles." J. Air and Waste Management Assoc., 45, 320-385.

In addition, liquid water absorbed by water-soluble species also constitutes a major component at high relative humidity (>70 percent), but standard techniques for measuring $PM_{2.5}$ and PM_{10} remove some of the water in the aerosol before measurement. Therefore, the measurements are not intended to include this water fraction.

Coarse particles (PM_{10}) are normally generated by grinding activities, and are dominated by material of geological origin, while geological materials often constitute a small portion (<10 percent) of the $PM_{2.5}$ mass concentrations. **Table 1** presents a list of the most commonly detected metals in various emission sources. Several of these have changed over time as they have been eliminated from the fuels (e.g., Pb as a gasoline additive) or been highly curtailed as industries have modernized.

The metals and their oxides are most often the direct emissions, including the black carbon which is abundant among the diesel soot. These are considered the primary particle emissions. Secondary particles usually are formed several hours or days following the emissions of gaseous precursors, and attain aerodynamic diameters between 0.1 and 1 micron. This accounts for the long-range transport of these pollutants.

Several of these particles are volatile and transfer mass between the gas and particle phase to maintain a chemical equilibrium. For example, VOCs may change into particles; the majority of these transformations result from photochemical reactions that also create high ground ozone levels or smog conditions[9]. Unlike the formation of sulfates and nitrates, for which the chemical formation mechanisms are well studied, understanding the mechanisms of gas to particle conversion and formation of secondary organic aerosols (SOA) is emerging. However, some empirical data on the aerosol formation potential are available in the literature, such as the "fractional aerosol coefficients" - the fraction of the precursor gas that will end up as aerosols[10]. Although these coefficients are only rough estimates, knowledge can be used to incorporate SOA into PM emissions inventory. In general, SOA (or organic carbon) ranges between 5 to 30 percent of the fine PM depending on the local fuel mix.

Meteorological conditions, which determine the dilution of pollutants, the rates of chemical reactions, and the removal processes such as dry and wet deposition, are important factors affecting the particle concentration in the ambient air[11]. In addition, formation rates of secondary aerosols depend on meteorological conditions (such as sunlight) and atmospheric chemistry (for example, the presence of ozone). Thus, concentrations of secondary aerosols may vary more than concentrations of primary aerosols.

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[9] Seinfeld, J. H. and Pandis, S. N. (1998). "Atmospheric Chemistry and Physics: From Air Pollution to Climate Change." John Wiley & Sons, New York. The chemical reactions leading to production and destruction of ozone via NOx and VOC's run into 100's and a number have documented this process. However, the conversion of gaseous pollutants to particles is still an area for research.

[10] Grosjean, D. and Seinfeld, J. H. (1989) "Parameterization of the formation potential of secondary organic aerosols." Atmospheric Environment, 23, 1733-1747. & Ulrike Dusek, IIASA, 2000, "Secondary Organic Aerosol – Formation Mechanisms and Source Contributions in Europe" @ http://www.iiasa.ac.at/~rains/reports/IR0066.pdf

[11] There are two dominant mechanisms responsible for the atmospheric loss of particles, wet and dry deposition. Larger particles tend to "dry" deposit due to a combination of gravitational settling and turbulent transport. Smaller particles, due to the reduced gravitational settling, are lost more via "wet" deposition (e.g., via rain). See "Fundamentals of Atmospheric Modeling" by Mark Jacobson, http://www.stanford.edu/group/efmh/FAMbook/FAMbook.html

What are the PM Pollution Sources, How Much?

Particulate pollution varies widely across developing country cities in composition, sources and spatial distribution. Besides local sources within urban areas, long-range transport of air pollution adds another dimension to the existing uncertainty in the assessment of PM sources and concentrations[12].

The range of pollution sources in developing country cities is typically wider than those observed in their industrial country counterparts. This is because of the rapid transition between rural and urban economies in many developing countries. The result has been that in rapidly developing urban areas sources include those typically thought of as rural (such as cooking with solid fuels) in addition to the sources typically thought of as urban (such as fossil fuel-based transportation and industry). In short, economic development typically results in more motor vehicles and more industry, which will result in greater PM pollution unless they are well controlled, but many developing country cities continue to have large fractions of traditional sources like biomass burning so air quality management programs also need to address these pollutants to be effective.


Old Vehicles


Fugitive dust


Coal and fuelwood sacs


Road dust


Industrial combustion


Garbage burning

It is important to note that the contribution of various sources to the emissions is not same as the contribution to the ambient concentrations. The elevated sources such as power plants and industries tend to be part of the long range transport and get deposited at places other than the source area where as the ground level sources, such as vehicular exhaust, domestic emissions, and fugitive emissions tend to contribute more at the local ambient levels. Hence, even though the fraction of ground based emissions might be small, their relative contribution to ambient levels can be high.

[12] For references on chemistry and modeling activities, refer to NARSTO @ http://www.narsto.org/section.src?SID=74

Bottom-Up – Emissions Source Contribution

Major sources of particulate emissions include: combustion processes (e.g., the burning of fossil fuels for steam and power generation, heating and household cooking with both traditional and modern fuels, and transportation; and agricultural burning), tilling, processing, animal husbandry, and various industrial processes. In most of the developing countries of Asia, Africa, and Latin America, coal, oil, and biomass remain important energy sources and contribute significantly to air pollution.

Further, pollution control measures are tightly linked with the economic activities and the feasibility of technology transfer. Several methods of controlling emissions are practiced in most developing country cities; including fuel switching to gas and low-sulfur coal, the more wide-scale use of district heating systems, use of flue-gas desulfurization, emission control equipment, energy-efficient installations, and the use of advanced combustion technologies. However, there are often large numbers of combustion sources that may be difficult to control, and the efficiency of these technologies and levels of emission control are low.

Sources frequently cited as among the most important contributors to pollution include: vehicles (via direct and indirect (e.g., fugitive dust) emissions), industrial activity, household fuel use, and the power sector[13].

In a growing number of developing country cities, motor vehicles are usually a major source of PM. Additionally, in some developing countries a relatively large proportion of motor vehicles are diesel powered which generate on the order of ten times more respirable particles than gasoline engines per vehicle kilometer traveled (VKT). **Table 2** presents a set of average emission factors for various vehicular types in the developing countries. Cars found in developing countries also tend to be older and in many cases they have not been required to meet clean emission standards. As a result, they tend to be more polluting.

Table 2: Average Emission Factors[14]

	Gasoline			Diesel				CNG			
	2Ws	3Ws	Cars	Cars	LDV	HDT	Bus	3Ws	Cars	LDV	Bus
PM_{10}	0.10	0.20	0.10	1.00	1.25	2.00	1.50	0.10	0.05	0.02	0.02
$PM_{2.5}$	0.05	0.08	0.03	0.60	0.50	1.00	0.80	0.05	0.02	0.01	0.01
SO_2	0.02	0.02	0.07	0.40	0.30	1.00	1.00	0.00	0.00	0.00	0.00
NO_x	0.15	0.10	0.20	1.25	2.00	10.0	10.0	0.35	0.20	3.50	2.50
CO	2.50	8.00	5.00	2.00	2.50	3.50	3.50	3.50	1.00	3.50	3.50
CO_2	40	80	200	250	500	850	850	70	100	450	450
HC	1.50	5.00	1.00	0.40	0.20	1.00	1.00	0.15	0.02	0.10	0.10
Authors assumptions based on a variety of sources; USE WITH DISCRETION											

[13] Fugitive dust is a non-point source air pollution. Significant sources include unpaved roads, crop land, and construction sites. The road dust is directly dependent on the vehicular activity and the silt loading on the paved and unpaved roads. In the developing country cities, the road dust fraction can be as high as 30 percent, due to constant resuspension. A tool to estimate the dust emissions is available @ http://urbanemissions.info/simair/Dust1.01.xls. The dust from the agriculture activities is seasonal.

[14] SIM Series 2008-002 "Four Simple Equations to Vehicular Emissions Inventory" @ http://www.urbanemissions.info/simair

In Africa, PM sources are dominated by biomass burning[15] and in some cases coal combustion, which is similar to temperate regions such as China and parts of Eastern Europe that depend on solid fuels for heating.

Sources such as industrial coal burning in boilers have been studied extensively, household cook stoves and their emission contribution are being studied, and some sources such as trash burning are not included in most inventories of emissions. **Figure 3** presents estimated source shares in PM_{10} emission inventories[16] for cities around the world and Totals are presented in **Table 3**. The results presented include only the in-city inventories and the long range transport of pollution, especially in neighborhoods downwind of a relatively distant pollution source, makes it difficult to pin point the contributions.

Table 3: Reported PM_{10} Emission Estimates for Urban Centers[17]

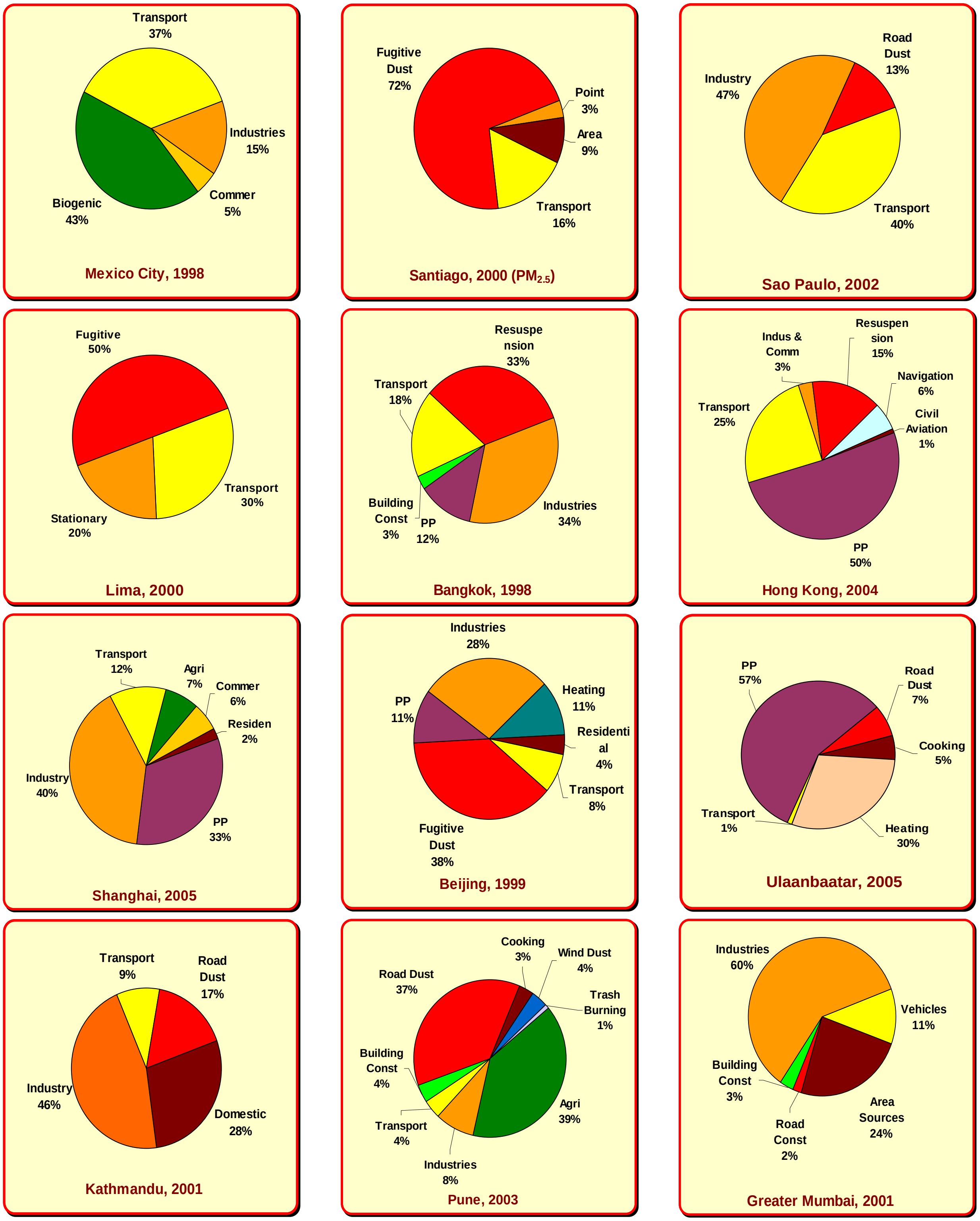
City, Country	Base Year	Emissions (ktons/yr)	Source
Sao Paulo, Brazil	2002	66	Prof. Paulo Artaxo, University of Sao Paulo, Brazil
Santiago, Chile	2000	10.6	Prof. Héctor Jorquera, Pontificia Universidad Católica de Chile, at GURME Presentation (2003)
Mexico City, Mexico	1998	21	Dr. Mario Molina et al., MIT at GURME Presentation (2003)
Lima, Peru	2000	23.9	Urban Air Pollution Control in Peru, ECON Report to The World Bank (2006)
Shanghai, China	2005	152.3	IES Program - Shanghai - http://www.epa.gov/ies/index.htm
Beijing, China	1999	55.4	IES Program - Beijing - http://www.epa.gov/ies/index.htm
Ulaanbaatar, Mongolia	2005	213.4	Urban Air Pollution Analysis for Ulaanbaatar, The World Bank (2007) @ www.urbanemissions.info
Bangkok, Thailand	1998	38.2	Thailand Environment Monitor 2002, The World Bank
Hong Kong,	2004	8.1	Hong Kong Environment Protection Department http://www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inve.html
Pune, India	2003	38.7	University of Pune - http://www.unipune.ernet.in/dept/env/;
Delhi, India	2000	150	TSP Emissions, Gurjar et al., 2004
Mumbai, India	2001	16.6	Bhanarkar et al., (2005)
Khatmandu, Nepal	2001	10.6	Kathmandu - Ph.D Thesis by Regmi Ram Prasad, Toyohashi University of Technology, Japan
Dhaka, Bangladesh	2005	10.2	Dr. Khaliquzzmann, The World Bank, Dhaka, Bangladesh

[15] Daniel Kammen "Cookstoves for the Developing World." http://socrates.berkeley.edu/~kammen/cookstoves.html

[16] An example equation to calculate emissions is $E = AL * EF$ where E = emissions (e.g., tons of SO_2 per year), AL = Activity level – for example amount of fuel used (e.g., tons of coal burnt per year), EF = Emission factor (e.g., tons of SO_2 emitted per ton of coal burnt). For vehicular emissions, similar equation would be $E = NV * EF * VKT$ where E = emissions (e.g., tons of PM_{10} per year), NV = Number of vehicles, VKT = vehicle kilometers traveled per year, EF = emission factor (e.g., gm/km or ton/km of PM_{10})

[17] Note that the information presented here is based on estimated emission inventories, which in turn are based on activity levels. As a result, the information is likely to miss a number of source categories. This is presented here to give readers an overview of the sources as they were calculated by various groups for multiple cities for multiple years with multiple uncertainties. Emission inventories such as these contain only primary PM_{10} emissions and do not account for secondary nitrates, sulfates, ammonium, and organic carbon. These inventories often used emission factors from industrialized countries and may not adequately represent emissions corresponding to the equipment, fuels, and operating conditions found in developing countries.

Figure 3: Estimated Contribution of Various Sectors to PM_{10} Emissions Inventory



There is no one single dominant pollution source that is common to all the cities listed in **Figure 3**. Direct vehicular emissions and road resuspension accounted for more than 50 percent for Sao Paulo in 2002, compared to 60 percent originating from industries for Greater Mumbai in 2001, and fugitive dust accounted for 72 percent in Santiago in 2000. Additionally, this mix of main sources is rapidly changing in these cities. In particular, cities such as Kathmandu and Jakarta, which are rapidly expanding, are increasingly experiencing problems related to transportation. Urban areas like Shanghai, Beijing, and others in China are increasingly dominated by industrial and power plant emissions, mainly due to burgeoning economic activity. One common source, road dust also referred as fugitive dust, is a growing source of predominantly coarse PM owing to unpaved roads and increased motorization.

Sources of PM in rural areas differ quite significantly from those observed in megacities. They are dominated by domestic sources, mainly stoves used for cooking, and in the colder climates, for space heating. For example in the yurts of Mongolia, where stoves are used for both cooking and heating for most of the year, domestic sources dominate[18]. Unprocessed biomass fuels (wood, dung, and crop residues) and fuels such as coal are common household energy sources in these countries, and they are high emitters of PM and a multitude of other pollutants. In general, these fuels are used in developing countries because of their availability and affordability and are known to emit more carcinogens which tend to worsen rural indoor environments more than urban outdoor environments[19]. The percent usage of biomass fuels and unprocessed fuels is lower, but not negligible, in urban centers[20].

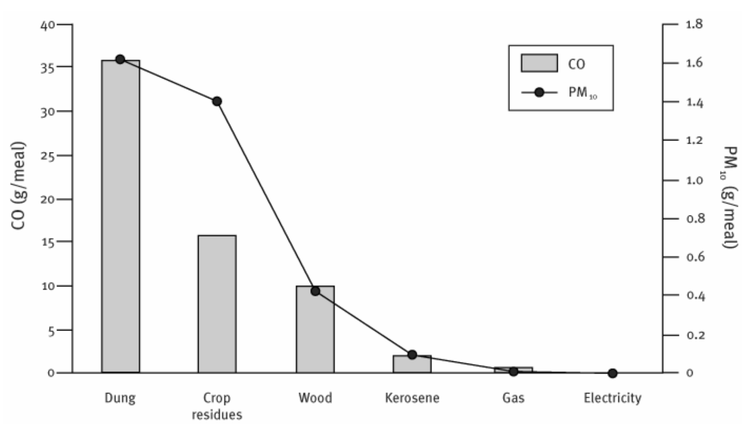


Figure 4: Emission Rates of CO and PM10 by Household Fuel[21]

In China, coal is burned in un-vented stoves, whereas in most of South Asia, kerosene is used in inexpensive stoves giving off high levels of PM emissions[22]. Africa's fuel

[18] Guttikunda, 2007, "Urban Air Pollution Analysis in Ulaanbaatar" @ http://www.urbanemissions.info/ulaanbaatar

[19] WHO, 2006. "Indoor air pollution and household energy." @ http://www.who.int/heli/risks/indoorair/indoorair/en/

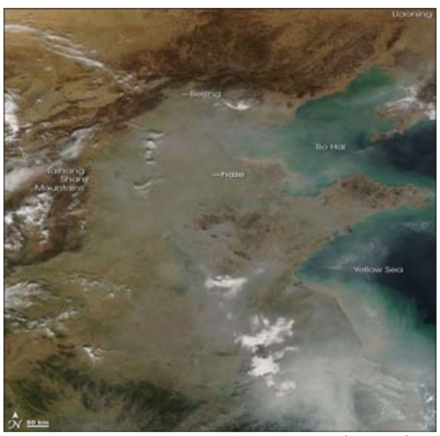
[20] Streets, D.G. et al., 2003. "Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions." Global Biogeochemical Cycles, 17(4). ISI:000186087000001.

[21] Practical Action Web Site. http://practicalaction.org/?id=smoke_report_3

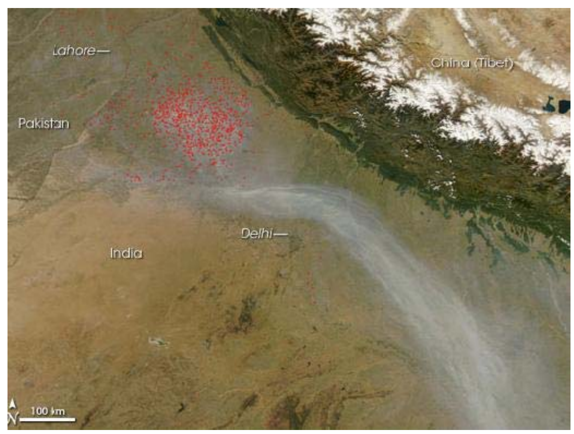
[22] Ritchie, I. M. 1983. Residential air pollution from kerosene heaters. J. Air Poll. Control Assoc. 33(9):879-881; Keyanpour-Rad, M. 2004. Toxic organic pollutants from kerosene space heaters in Iran. Inhal. Toxicol. 16(3):155-157;

consumption drives the use of biomass fuels such as wood, which has led to problems of deforestation in some sub-Saharan African regions. Wood fulfills the cooking fuel needs of some 90% of the urban households in Africa, and is probably as high if not higher in rural areas[23]. The use of poor quality biomass fuels decreases with development, thus the least developed areas are most likely to experience the highest levels of air pollution. **Figure 4** presents emission rates of PM_{10} by fuels commonly used in the rural parts of Asia and Africa. On average, cooking stove emissions decrease as the fuel source moves from use of dung/crop residues to fuel wood to charcoal to kerosene to LPG/natural gas/electricity. Most of the time, during a bottom-up emission inventory process, rural sources are either not included or underestimated due to lack of data on consumption patterns.

Natural phenomena also cause a considerable amount of air pollution. One of the major natural sources of air pollution is volcanic activity, which at times spews large amounts of ash and toxic fumes into the atmosphere. In addition to large amounts of PM, it releases gases such as SO_2 and NO_x that form secondary PM. Though seasonal, dust storms in deserts and arid regions and smoke from forest and grass fires also contribute substantially to PM pollution. Due to the magnitude of the impact of these events, pollution due to natural phenomena is more of a regional concern than an urban issue. However, the dust blown from the Sahara desert has been detected in West Indian islands[24]. Furthermore, the spring dust blown from the Gobi desert[25] has been detected across the Atlantic Ocean days after passing over the Pacific Ocean and during Northern American transit raising PM levels above WHO guidelines[26].



Haze over eastern China (2006)



Haze over Northern India (2008)

Cheng, Y. S., et al., 2001. Chemical composition of aerosols from kerosene heaters burning jet fuel. Aerosol Sci. Technol. 35(6)L949-957.

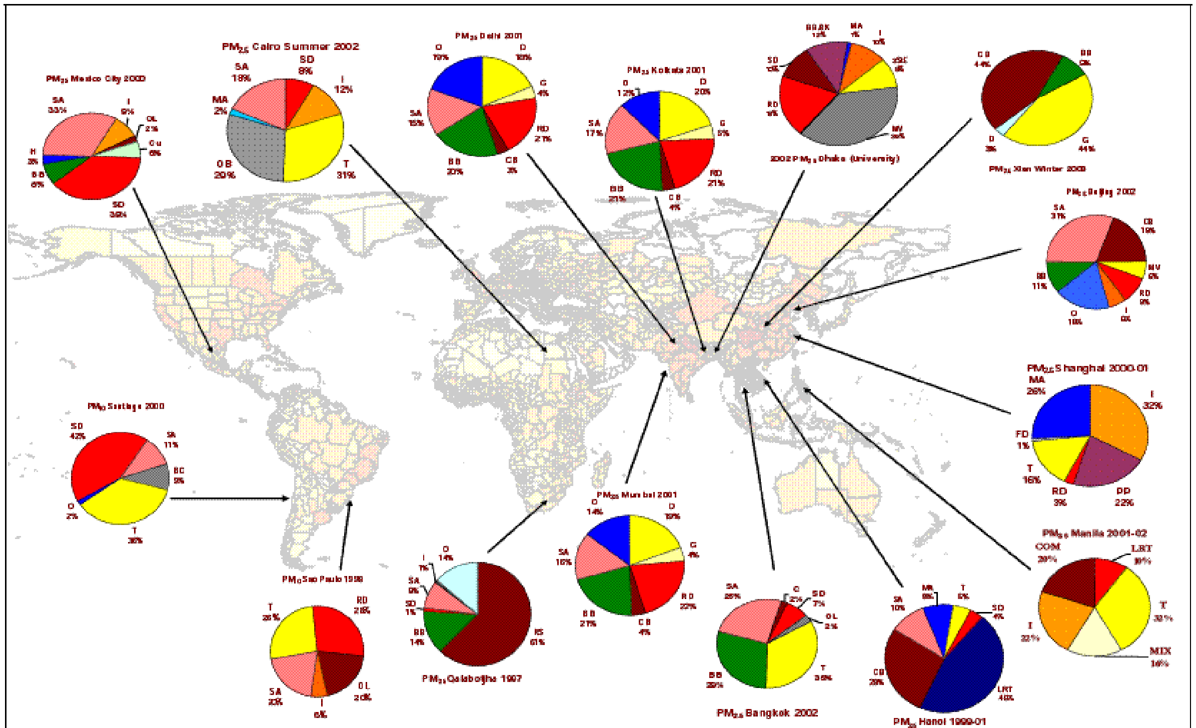
23 ESMAP, 2002. "Energy and Poverty Reduction: Proceedings from a Multi-Sector and Multi-Stakeholder Workshop: How can Modern Energy Services Contribute to Poverty Reduction?" Addis Ababa, Ethiopia, October 23-25, 2002. Ezzati. M., and D. M. Kammen, 2002. "Evaluating the health benefits of transitions in household energy technologies in Kenya." Energy Policy, 30, 815–826.

24 Africa to Atlantic, Dust to Dust - http://www.gsfc.nasa.gov/feature/2004/0116dust.html

25 In April 1998, one the strongest dust storms, documented at http://capita.wustl.edu/Asia-FarEast/ crossed the Pacific and Atlantic Oceans in a period of 10 days; Haze over Eastern China – Observations of November 6th, 2006 http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13953.
Haze over Northern India – Observations of November 5th 2008,
http://www.nasa.gov/mission_pages/fires/main/world/indiafire_20081105a.html

26 Jaffe D.A., et al., 1999. "Transport of Asian Air Pollution to North America." Geophys.Res.Letts. 26, 711-714. &
Task Force on Hemispheric Transport of Air Pollution @ http://www.htap.org/
Overseas Pollution Hitting The U.S. - http://www.sciencedaily.com/videos/2008/0710-overseas_pollution_hitting_the_us.htm

During these dust storm periods, PM measurements of over 1000 μg/m^3 were recorded in Northeast China and Mongolia. It should be noted that dust storms and burning are not necessarily natural phenomena. Desert crusts and vegetation can be destroyed by livestock and vehicles, thereby creating a reservoir of suspendable dust during high winds. Additionally, vast amounts of central Africa, South America, and Indonesia are burned to clear land for planting. These anthropogenic activities compound the impact of what might otherwise be viewed as purely natural phenomena, and they may change the importance of these pollution sources within the context of an air quality management program.



BB=Biomass Burning; CB = Coal Burning; D=Diesel; G=Gasoline; RD=Road Dust; Sa=Secondary Aerosols; O=Others; I=Industry; MV=Motor Vehicles; T=Transport; OL=Oil Burning; SD=Soil Dust; BC=Black Carbon; Cu=Copper; H=Hydrogen; RS=Residential; LRT=Long Range Transport; MA=Marine; PP=Power Plant; FD=Fugitive Dust; 2StE=2-Stroke Engine; BK=Brick Kiln; C=Construction

Figure 5: Summary of PM Source Apportionment Studies Around the World[27]

Figure 5 presents the results of fifteen source apportionment[28] case studies conducted in developing country urban areas across the globe – this method. Many other receptor model

[27] Practical Action Web Site. http://practicalaction.org/?id=smoke_report_3

[28] The Source Apportionment methodology is based on the ambient measurements followed by chemical analysis to identify characteristic patterns or profiles of air pollution – in other words, reverse of Table 1. For example, iron and steel mills release particulate matter that is rich in iron, cement plants emit aerosol containing calcium, and diesel exhaust contains largely carbonaceous aerosol. In general, specific elements, such as metals, can serve as tracers of pollution from different industrial processes. The combustion of gasoline and other hydrocarbon fuels in automobiles, trucks, and jet airplanes produces several primary pollutants: nitrogen oxides, gaseous hydrocarbons, and carbon monoxide, as well as large quantities of particulates. Petroleum refineries (particularly older ones) may be responsible for extensive hydrocarbon and particulate pollution. Source apportionment aims to explain the chemical composition of contributions from different sources. In doing so, source apportionment quantifies the relative contributions of these different sources.

studies are referenced in the bibliography. The cases were conducted by a wide variety of universities and government agencies, and the motives for the studies varied widely. For example, the Qalabotjha, South Africa study was conducted exclusively for policy decisions on energy use in the urban area. The objective was to convince authorities to subsidize electrification of townships as a way of reducing residential coal use (low-grade coal is by far the least expensive form of energy in South Africa). The source apportionment study confirmed that residential coal combustion was by far the greatest source of air pollution, accounting for 61 percent of $PM_{2.5}$ and 43 percent of PM_{10} at the three Qalabotjha monitoring sites. In contrast, the Shanghai project developed source profiles representative of Shanghai, such as small and medium size boilers, cement kilns, and dust on representative roads. These source profiles are available for future air pollution studies.

The most common source identified in most of the urban areas was dust emissions. Dust sources include: resuspended dust from paved roads, unpaved roads, construction, demolition, dismantling, renovation activities, and disturbed areas. When dust sources are caused by sporadic or widespread activities due to wind or vehicle travel, they can often be difficult to quantify.

In summary, by any method, the main sources of pollution remain the same, industrial combustion, domestic heating and cooking, transport (direct and indirect), biomass burning, and some natural sources. How much comes from which source depends entirely on the city consumption patterns and only a scientifically sound analysis can reveal the contributions.

Particulate Pollution & Health Impacts

Epidemiological studies in industrial and developing countries have shown that elevated ambient PM levels lead to an increased risk of mortality and morbidity.[29] Health effects range from minor irritation of eyes and the upper respiratory system to chronic respiratory disease, heart disease, lung cancer, and death. Air pollution has been shown to cause acute respiratory infections in children and chronic bronchitis in adults. It has also been shown to worsen the condition of people with preexisting heart or lung disease. Among asthmatics, air pollution has been shown to aggravate the frequency and severity of attacks. Both short-term and long-term exposures have also been linked with premature mortality and reduced life expectancy.

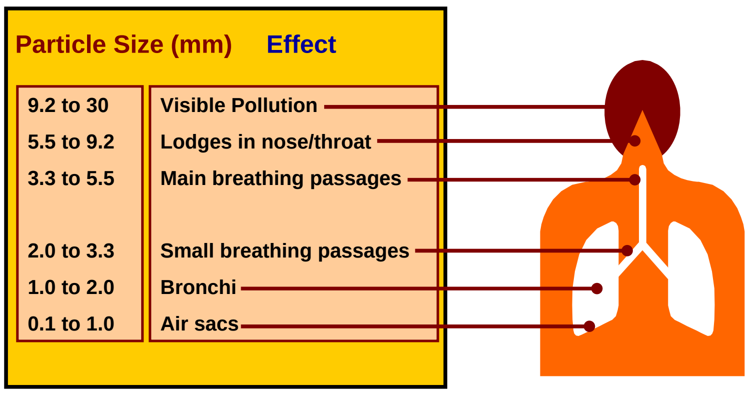


Figure 6: Effects of PM on Human Health

The health impacts of air pollution depend on the pollutant type, its concentration in the air, length of exposure, other pollutants in the air, and individual susceptibility[30]. The undernourished, very young and very old, and people with preexisting respiratory disease and other ill health, may be more affected by the same concentrations than healthy people. Additionally, developing country poor tend to live and work in the most heavily polluted areas. They are more likely to cook with dirtier fuels resulting in higher levels of indoor and outdoor air pollution. As a result, their elevated risk due to health factors is exacerbated by their increased exposure to PM.

Numerous studies suggest that health effects can occur at PM levels that are at or below permitted national and international air quality standards[31] and according to WHO[32], there is no clear evidence for a threshold below which PM pollution does not induce some adverse health effects, especially for the more susceptible populations – children and the elderly. This situation has prompted a vigorous debate about whether current air quality standards are sufficient to protect public health and reduce damage costs[33]. **Table 4** provides a sense of range of estimated PM exposure/mortality dose responses reported in a

[29] See Health Effects Institute (HEI) @ http://www.healtheffects.org

[30] For a review article see Pope and Dockery (2006).

[31] U.S. EPA. 2006. Provisional assessment of recent studies on health effects of particulate matter exposure. EPA/600/R-06/063. http://www.epa.gov/PM/pdfs/ord_report_20060720.pdf

[32] WHO @ http://www.emro.who.int/Ceha/pdf/Transport.pdf

[33] WHO challenges world to improve air quality – www.who.int/mediacentre/news/releases/2006/pr52/en

comprehensive review of recent studies[34]. For short-term exposures Pope and Dockery (2006) conclude

It seems unlikely that relatively small elevations in exposure to particulate air pollution over short periods of only 1 or a few days could be responsible for very large increases in death. In fact, these studies of mortality and short-term daily changes in PM are observing small effects (p. 713).

However as one would expect, the impact of longer-term exposure is more dramatic. The estimated annual mortality increase from a 10 $\mu g/m^3$ increase in long-term exposure to $PM_{2.5}$ is estimated to average around 6 percent[35].

Table 2: Average dose response functions for morbidity end points[36]

Morbidity Health Endpoint	Dose response function (β) (effects/1μg/m³ change/per capita)
Adult Chronic Bronchitis	0.000040
Child Acute Bronchitis	0.000544
Respiratory Hospital .Admission	0.000012
Cardiac Hospital Admission	0.000005
Emergency Room Visit	0.000235
Asthma Attacks	0.002900
Restricted Activity Days	0.038280
Respiratory Symptom Days	0.183000

These are average functions (authors interpretation); Use with discretion

Studies in India, for instance, have shown that acute respiratory infection (ARI) in children under 5 is the largest single disease category in the country, accounting for about 13 percent of the national burden of disease,[37] and children living in households using solid fuels have 2-3 times more risk of ARI than unexposed children. In 1995, air pollution in China from fuel combustion was estimated to have caused 218,000 premature deaths (equivalent to 2.9 million life-years lost), 2 million new cases of chronic bronchitis, 1.9 billion additional restricted activity days, and nearly 6 billion additional cases of respiratory symptoms and the new estimates suggest the premature mortality rates are as high as 300,000 for the current urban pollution trends. The culprit pollutant in both China and India is believed to be fine PM. While estimates of health impacts are effective in raising overall concern about air quality, they do not specifically answer the question of the sources of fine PM, nor what measures should be taken to reduce the impacts associated with exposure.

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[34] Pope, C. A., III and Dockery, D. W. 2006. Health effects of fine particulate air pollution: Lines that connect. Journal of the Air Waste Management Assoc. 56(6):709-742;
Bell, et al., 2006. "The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City." Environmental Research, 100, March 2006, 431-440;
Li, J., and S. K. Guttikunda, et. al., 2004. "Quantifying the Human Health Benefits of Curbing Air Pollution in Shanghai." Journal of Environmental Management. 70, pp. 49-62;
HEI, 2004. "Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review." Health Effects Institute, Boston, USA;
"Cost of Pollution in China", East and Pacific Region, The World Bank, Washington DC - http://go.worldbank.org/FFCJVBTP40

[35] PAPA – Public Health and Air Pollution in Asia - http://www.cleanairnet.org/caiasia/1412/article-48844.html &
From presentation by Dr. Sumi Mehta, Health Effects Institute, "Emerging Evidence on the Health Effects of Air Pollution in Asia" @ http://baq2008.org/spa-mehta

[36] SIM Series 2008-006 "Estimating Health Impacts of Urban Air Pollution" @ http://www.urbanemissions.info/simair

[37] Comparative Quantification of Health Risks - http://www.who.int/publications/cra/en/

Particulate Pollution & Environmental Impacts

While health effects drive most of the concern about air quality in developing countries, PM also affects regional and global atmospheric chemistry and the radiation balance[38]. Aerosol particles scatter and absorb solar radiation, and also alter the formation of cloud droplets. These physical interactions change the earth's radiation balance, affecting local and global temperatures and possibly precipitation.

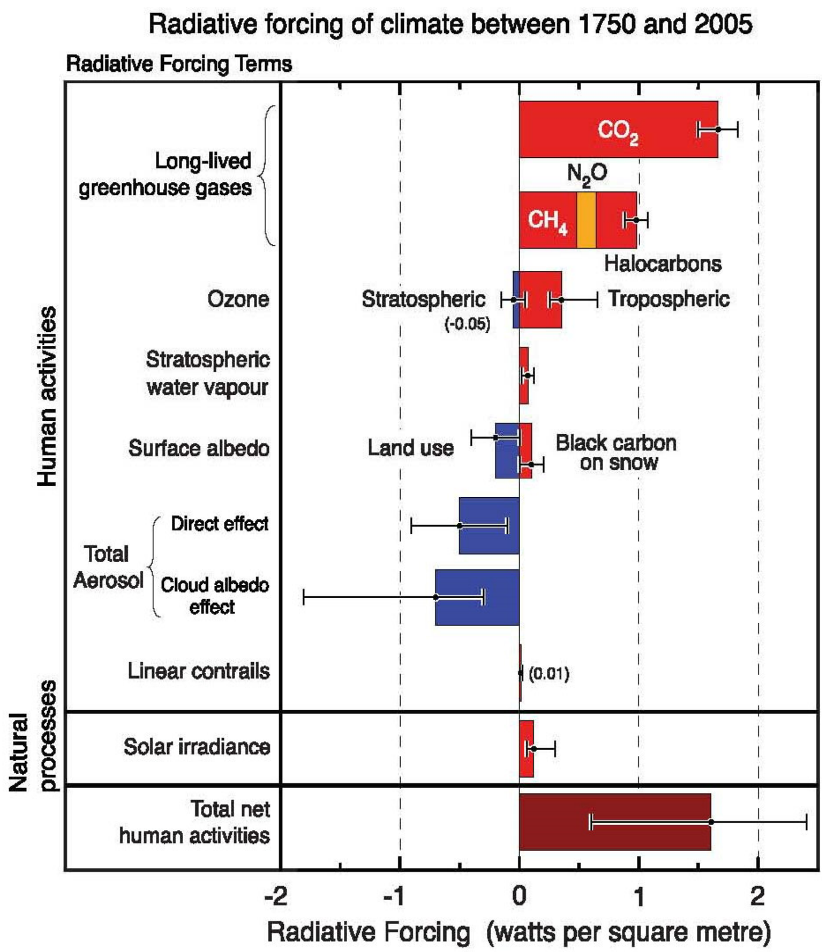

Figure 7: Radiative Forcing of Climate Between 1750 and 2005[39]

Figure 7 summarizes the radiative forcing of greenhouse gases (GHGs) and various types of aerosols. The figure shows that although GHGs are quite important in the overall picture, pollutants that are usually considered only in the air quality domain, such as aerosols and ozone, also affect climate change. The understanding of the impact of aerosols on the climate system and how to evaluate this impact for policy relevant issues is very low.

[38] Role Of Aerosols In Climate Change Examined @ http://www.sciencedaily.com/releases/2008/09/080905153801.htm
[39] Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis, Summary for Policymakers*.

Research continues to assess the effects of many different types of aerosols on climate under different conditions[40].

PM pollution can also impact visibility in urban centers. Mountains or buildings once in plain sight can suddenly be blocked from view. Air pollution that reduces visibility is often called haze or smog[41 42]. The term smog originally meant a mixture of smoke and fog in the air, but today it refers to any visible mixture of air pollution. The incidents of haze and smog in cities are increasing, which typically starts in cities and travels with the wind to appear in the more remote areas. One consequence of smog over any given area is that it can change the area's climate. Certain dark particles, such as carbon, absorb solar radiation and scatter sunlight, helping produce the characteristic haze that is filling the skies over the world's megacities and reducing visibility. Figure 2.4 presents visibility on the roads of Bangkok. For the last four decades visibility reduced from 14 km to 7 km. During this period the number of vehicles quadrupled.

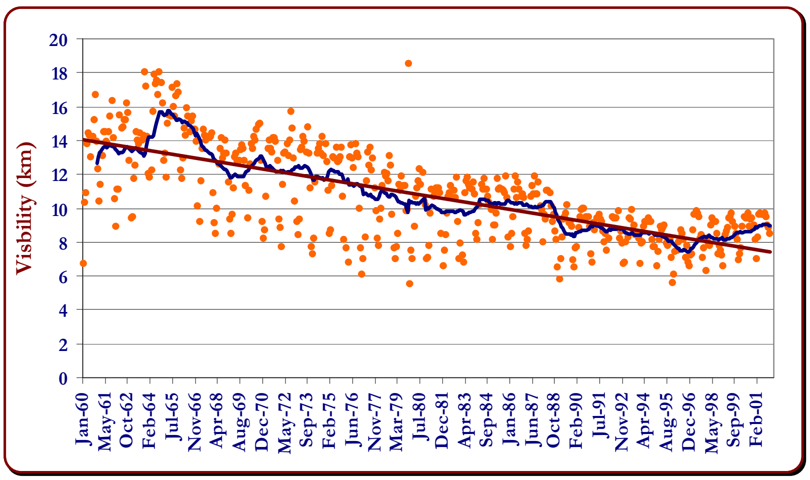

Figure 8: Measured Visibility on The Roads of Bangkok[43]

Particulate Pollution & Policy Implications

Policymakers in rapidly growing urban areas increasingly recognize that addressing air quality issues is an urgent priority. Studies and dialogues should include properly identifying the sources of pollution to formulate rational and effective policies and make informed investment decisions related to air quality improvements.

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[40] Menon, S.; Hansen, J.E.; Nazarenko, L.; and Luo, Y. (2002). "Climate effects of black carbon aerosols in China and India." Science, 297(5590):2250-2252;
Venkataraman, C.; Habib, G.; Eiguren-Fernandez, A.; Miguel, A.H.; and Friedlander, S.K. (2005). "Residential biofuels in South Asia: Carbonaceous aerosol emissions and climate impacts." Science, 307(Mar.):1454-1456;
Andreae, M.O. 2001. "The dark side of aerosols." Nature. 409 (6821):671-672;
Black Carbon Pollution Emerges As Major Player In Global Warming @ http://www.sciencedaily.com/releases/2008/03/080323210225.htm

[41] Chemists Find New Important Contributor To Urban Smog @ http://www.sciencedaily.com/releases/2008/03/080320150032.htm

[42] Watson, J.G. (2002) "Visibility: Science and regulation." J. Air Waste Manage. Assoc. 52(6):628-713.

[43] Pollution Control Department, Bangkok, Thailand