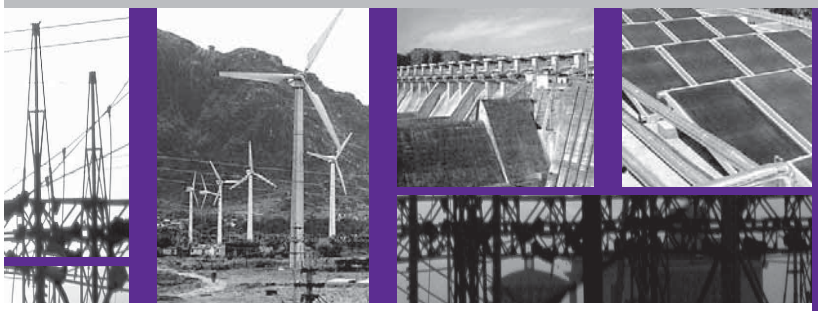
Formal Report 339/11



Tools for Improving Air Quality Management

March 2011

ESMAP

Energy Sector Management Assistance Program

Energy Sector Management Assistance Program (ESMAP)

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Tools for Improving Air Quality Management

A Review of Top-down Source Apportionment Techniques and Their Application in Developing Countries

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Contents

Boxes

Figures

Tables

Acknowledgments

This report describes the results of a three-year study and technical assistance project on source apportionment of particulate pollution in developing counties that was undertaken by the Environment Department (ENV) of the World Bank. The financial and technical support by the Energy Sector Management Assistance Program (ESMAP) is gratefully acknowledged.

This report was prepared by a team led by Todd M. Johnson, and consisting of Sarath Guttikunda, formerly with the Environment Department, World Bank, and Gary J. Wells, Professor, Clemson University. Major contributions and overall guidance for the study was provided by an expert advisory panel comprised of Paulo Artaxo of the University of Sao Paulo, Brazil; Tami C. Bond of the University of Illinois at Urbana-Champaign; Armistead G. Russell of Georgia Tech University; John G. Watson of the Desert Research Institute; and Jason West of the University of North Carolina at Chapel Hill.

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The team completed its work in early 2008 and the final report was submitted for publication in July of the same year. After undergoing a series of internal and external reviews, the report was put into production under the publishing guidance of ESMAP. Although the authors note that this report includes information and references up to the end of 2007, the report's overall findings and conclusions remain valid.

This report was edited and typeset by Shepherd, Inc. Ms. Marjorie K. Araya (ESMAP) carried out comprehensive proofreading, coordinated the production of the final report and its dissemination. Special thanks to Jeffrey Lecksell, World Bank Map Unit.

Abbreviations and Acronyms

AAS	atomic absorption spectrophotometry
ACE-Asia	Asia Pacific Regional Aerosol Characterization Experiment
APCA	absolute principal component analysis
AQMS	air quality management system
BAM	beta attenuation monitor
BC	black carbon
CAMMS	pressure drop tape sampler
CFC	chlorofluorocarbons
CMB	chemical mass balance
CO	carbon monoxide
CO_2	carbon dioxide
COPREM	constrained physical receptor model
Dichot	dichotomous sampler
EC	elemental carbon
EF	enrichment factor
EPA	U.S. Environmental Protection Agency
ESMAP	Energy Sector Management Assistance Program
FRM	federal reference method
GAINS	greenhouse gas and air pollution interactions and synergies
GC	gas chromatography
GHG	greenhouse gas
HPLC	high performance liquid chromatography
IBA	ion beam analysis
IC	ion chromatography
ICP	inductively coupled plasma
IES	integrated environmental strategies
IMPROVE	interagency monitoring of protected visual environments
INAA	instrumental neutron activation analysis
INDOEX	indian ocean experiment
MS	mass spectrometer
MiniVol™	MiniVol™ portable air sampler
MLR	multi linear regression
µm	micron
NASA	U.S. National Aeronautics Space Administration
NH_3	ammonia
NIOSH	U.S. National Institute for Occupational Safety and Health
NOx	nitrogen oxides

OC	organic carbon
O_3	ozone
PAH	polycyclic aromatic hydrocarbons
PCA	principal components analysis
PESA	proton elastic scattering analysis
PIGE	particle induced γ-ray emission
PIXE	proton induced x-ray emissions
PM	particulate matter
PM_{10}	coarse particulate matter with diameter < 10µm
$PM_{2.5}$	fine particulate matter with diameter < 2.5µm
$PM_{0.1}$	ultra-fine articulate matter with diameter < 0.1µm
PMF	positive matrix factorization
PP	power plant
PSCF	potential source contribution function
SOA	secondary organic aerosols
SPM	suspended particulate matter
SO_2	sulfur dioxide
TEOM®	tapered element oscillating microbalance
TOR	thermal optical reflectance
TOT	thermal optical transmittance
TSP	total suspended particulates
VKT	vehicle kilometer traveled
VOC	volatile organic compounds
WB	World Bank
WHO	World Health Organization
XRF	x-ray fluorescence
$\mu g/m^3$	micro-grams per cubic meter

Executive Summary

Building an effective air quality management system (AQMS) requires a process of continual improvement, and the **source apportionment** techniques described in this report can contribute in a cost effective manner to improving existing systems or even as the first step to begin an AQMS. This is good news for many developing country cities where the combination of rapid growth, dirty fuels, and old and polluting technologies are overwhelming the capacities of cities to control air pollution. For these cities, source apportionment offers policymakers practical tools for identifying and quantifying the different sources of air pollution, and thereby increasing the ability to put in place effective policy measures to reduce air pollution to acceptable levels.

This report arises from a concern over the lack of objective and scientifically-based information on the contributions of different sources of air pollution—especially for fine **particulate matter** (PM)—in developing countries. PM is the air pollutant of most concern for adverse health effects, and in urban areas alone accounts for approximately 800,000 premature deaths worldwide each year.

There are currently two basic approaches to determining the sources of air pollution and specifically, PM: (1) top-down or receptor-based source apportionment methods, and (2) bottom-up or source-based methods. The top-down approach begins by taking air samples in a given area (i.e., via air sampling receptors) and comparing the chemical and physical properties of the sample to the properties of emission sources. Top-down methods offer the promise of providing information on the types of emission sources and their relative contributions to measured air pollution, which in turn helps identify and quantify the sources that would be most effective to control. Advances in sampling and analytic techniques have made source apportionment a logical and cost-effective alternative for developing country cities.

Bottom-up methods begin by identifying pollution sources and estimating emission factors using dispersion models. Utilizing this information and detailed meteorological data an atmospheric dispersion model estimates ambient pollution levels. While bottom-up analysis can provide useful information for air quality management, there are practical reasons to expect inaccuracies. Among the major drawbacks of bottom-up methods are inaccurate or limited knowledge of meteorological conditions, and more fundamentally, the inability to account for unexpected sources, including the long-range transport of pollutants from outside the governing authority, which can provide a challenge in developing an effective air quality management system, and area sources such as biomass or trash burning. If a pollution source is not in the bottom-up analysis from the beginning, it will not emerge as a pollution source in the results. Bottom-up models also typically depend on information supplied by the pollution sources, such as industry or power plants. However, in order to avoid fines or cleanup expenses, polluters have an incentive to hide the seriousness of their pollution. Relatively simple and initially inexpensive top-down analyses can help identify and remediate these inaccuracies and an iterative approach of utilizing top-down and bottom-up techniques can improve the quality of the results of both methods.

Top-down source apportionment methods are based on the fact that PM sources often exhibit characteristic chemical patterns or profiles of air pollution. For example, iron and steel mills emit PM that is rich in iron, cement plants emit PM containing calcium, and diesel exhaust contains largely carbonaceous PM. In some cases, specific trace elements, such as metals, can serve as tracers for specific sources. A source apportionment analysis uses outdoor samples of PM and these chemical "fingerprints" of different pollution sources to estimate the contribution of these sources to the total PM problem.

A key component needed to conduct a top-down analysis is a collection of "source profiles" of the emission sources that are impacting the urban area being studied. A source profile identifies the chemical fingerprint emitted from individual sources. The more accurate a source profile is, the more likely that accurate results will follow. In a city's early applications of source apportionment, profiles from cities with similar source characteristics can be utilized, but as the analysis becomes more complex, local source profiles should be developed. Source profiles can be measured using the same methods to acquire ambient samples; this is often more cost-effective and accurate than individual emission tests.

This report summarizes the ways and means of conducting top-down, source apportionment analyses. Source apportionment methods are shown as a hierarchy, whereby cities can first use simple and inexpensive methods to achieve a broad understanding of the sources of PM. Later, more detailed and consequently more expensive methods can be used to improve understanding and accuracy. This report also presents results for 14 case studies conducted in 18 developing country cities over the past 5-8 years. As an example, the Qalabotjha, South Africa case found that residential coal combustion is by far the greatest source of air pollution in the region. The resulting policy recommendation was to subsidize the electrification of townships as a way to reduce residential coal use and atmospheric pollution. In Shanghai, China source profiles representative of Shanghai were developed, including for small and medium-size boilers, cement kilns, and road dust. These source profiles are now available for further air pollution studies and reflect the continual improvement of Shanghai's AQMS.

Multiple top down analyses can also be done for a city to reflect seasonal variations (e.g., summer versus winter or rainy versus dry). For example, in Xi'an, China, winter coal use contributed 44 percent of the carbonaceous sample, yet domestic coal burning was not an important contributor outside the heating season. Additional analyses in Xi'an found that long range transport from neighboring fast growing areas is an important contributing source of air pollution for the city. Such analysis results provide local authorities evidence that can be used when pressing regional and/or national authorities for stricter emission standards outside the governing authority's jurisdiction. In Bangkok, the contribution of biomass combustion to ambient fine PM was very high during the dry season due to the burning of rice straw in the city vicinity.

In the case studies, source apportionment analysis was found to be a cost-effective way of identifying contributors to the areas' air pollution. In many instances the source apportionment results provided new information on the sources of emissions as well as a quantitative estimate of the source contribution. Among the emission sources identified by source apportionment techniques that had been overlooked using the bottom-up models were secondary particulates such as sulfates that are often transported over long distances and area sources including biomass and refuse burning; in some cases these emissions accounted for a dominant share of the total air pollution.

Policymakers in rapidly growing urban areas recognize that correctly identifying the sources of air pollution is a vital first step in establishing efficient air pollution control policies. Top-down source apportionment, combined with bottom-up emission inventory techniques, should become a key element for supplying reliable, science-based pollution source data to a well designed AQMS.

Additionally, because of the expected long-term growth of energy use in developing country cities, governing authorities may be able to find allies to assist in building an effective AQMS via the source apportionment techniques presented in this report. An example is partnering with those interested in reducing greenhouse gases. Another example is a policy that reduces automotive air pollution by reducing the modal share of automobiles.

In developing effective air quality management systems, overcoming knowledge gaps is critical. Fortunately, a wealth of new data on $PM_{2.5}$ and PM_{10} constituents, pollution trends, main sources, and pollution chemistry, is becoming available on a routine basis as the results of new bottom-up and top-down analyses are published. This new information along with a growing commitment to utilizing scientifically-based analytical techniques within the framework of sound air quality management systems offers developing countries the hope of gaining control over the significant air pollution challenges that accompany rapid urban area development.

Report Summary

Worldwide, urban population is expected to grow from 2.9 billion in 2000 to 5 billion by 2030. Unless steps are taken, the declining air quality in many developing country cities suggests that as the population continues to grow, air quality will further deteriorate. The impacts will likely be particularly severe in developing country mega cities (cities with a population of more than 10 million). The potential for these rapid changes coupled with a growing demand for cleaner air leaves policymakers facing the need to improve their ability to control air pollution. Fortunately, in recent years major advances have been made in techniques utilized to estimate ambient air pollution levels and identify emission sources. These advances, which are discussed in this report, offer the opportunity for developing countries to implement sophisticated air quality management programs earlier in their development process than was accomplished by their industrial country counterparts.

Being able to identify different air pollution sources accurately is a key element in an effective air quality management system (AQMS). An AQMS brings together the scientific activities of determining air pollution emissions, ambient concentrations by pollution type, and resulting health impacts with political and regulatory aspects to formulate a society's reaction to air pollution. This report arises from a concern over the lack of information about the sources of ambient air pollution in developing countries—especially for fine **particulate matter** (PM), which is the major contributor to the adverse health effects of air pollution. Without reliable and accurate source information it is difficult for policymakers to formulate rational, effective policies and investments aimed at improving air quality. This report details source apportionment of PM as one method that is especially relevant to developing countries that need quantitative information on the sources of air pollution.

There are currently two fundamental approaches to determining and quantifying the contribution of air pollution sources: (1) top-down or receptor-based source apportionment; and (2) bottom-up or source-based methods. The top-down approach begins by sampling air in a given area and inferring the likely pollution sources by matching common chemical and physical characteristics between source and air pollution samples. Top-down methods offer the promise of quantifying the relative contributions of the different sources to ambient air pollution, where rather little may be currently known. Additionally, top-down methods often require few atmospheric measurements and relatively simple analysis. Bottom-up models begin by identifying pollution sources and their emission factors and then using meteorological patterns to predict ambient pollution levels and compositions. Major limitations of bottom-up approaches are that they are not derived from air pollution samples and the sources of pollution must be pre-identified. Ideally, top-down and bottom-up approaches should agree, but this is rarely the case for an initial application. However, proper analysis of the nature of the disagreement can result in improvements to both methods, and acceptable agreement is often achieved after several iterations. Together, these methods can provide confidence that the correct pollution sources have been targeted *before* instituting expensive air pollution control strategies.

Both top-down and bottom-up methods are discussed in this report, but the report concentrates on the former as a way to supplement and improve the results of the more traditionally utilized bottom-up methods. The top-down approach can support or call into question the validity of the assumed sources of air pollution in the bottom-up approach, and do so through actual samples of urban air pollution. In urban areas where little may be known about local air pollution, inexpensive, simple top-down techniques can quickly provide useful information on the relative importance of different sources of pollution. Through time more advanced top-down techniques can be implemented to give more certainty in the results and to test results gained via a bottom-up analysis.

The main objectives of this study are to review, demonstrate, and evaluate top-down methods to assess and monitor the sources of PM, using a combination of ground-based monitoring and source apportionment techniques referred to as receptor-based methods. These methods offer a cost effective opportunity for urban areas located in developing countries to improve their AQMS by providing an indication of the relative contributions of different, often previously unidentified sources of ambient air pollution.

The ultimate objectives of this report are to: (1) provide environmental institutions a guide to practical methods of receptor-based source apportionment (i.e., top-down methods); (2) communicate to policymakers the advantages of top-down methods and how they can be used effectively with or without bottom-up methods in an AQMS; and (3) disseminate broadly the findings and conclusions within the scientific and local/national environmental communities. In order to accomplish these objectives it is necessary to describe the nature and consequences of the major air pollution problem: particulate matter. Because of the seriousness of PM pollution for human health, visibility, climate, and materials damage, this report focuses solely on this type of pollution, while attempting to remain general enough to be applicable to a wider range of air pollutants.

Nature and Consequences of Particulate Matter

Particles in the air are classified by aerodynamic diameter size and chemical composition, and are often referred to as PM or aerosols. PM is generally measured in terms of the mass concentration of particles within certain size classes: total suspended particulates (TSP), PM_{10} or coarse (with an aerodynamic diameter of less than 10 micron), $PM_{2.5}$ or fine (with an aerodynamic diameter of less than 2.5 micron), and ultra fine particles (those with a diameter of less than 0.1 micron). The distinction between the coarse and fine particles is important because they have different sources, formation mechanisms, composition, atmospheric life spans, spatial distribution, indoor-outdoor ratios, temporal variability, and health impacts. Some PM occurs naturally, originating from dust storms, forest and grassland fires, living vegetation, sea spray, and volcanoes, and some PM originates as a result of human activities, such as fossil fuel combustion, industrial emissions, and land use.

In terms of mechanisms of formation, PM can be classified into two categories, primary and secondary particles. Primary particles are emitted directly into the atmosphere from a number of manmade and natural sources such as fuel combustion, biomass burning, industrial activities, road dust, sea spray, volcanic activity, and windblown soil. Secondary particles are formed through the chemical transformation of gaseous primary pollutants such as sulfur dioxide (SO_2), nitrous oxides (NO_x), certain volatile organic compounds (VOCs), and ammonia (NH_3). The resulting secondary particles are usually formed over several hours or days and usually fall within the fine PM range. This small size allows these pollutants to be transported over very long distances. Some of these particles are volatile and move between gaseous and particle phases. For example, VOCs may change into secondary particles through photochemical reactions that also create ground-level ozone or smog conditions. Ambient concentrations of secondary particles

are not necessarily proportional to quantities of primary gaseous emissions since the rate at which particles form may be limited by factors other than the concentrations of the precursor gases (e.g., temperature and relative humidity). By measuring the ambient concentrations of PM directly, receptor-based source apportionment techniques can help identify the sources of both primary and secondary PM.

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. There is little evidence that there is a threshold below which PM pollution does not have adverse health effects, especially for the most susceptible populations—children and the elderly. The adverse health impacts of air pollution can be substantial. For example in China in 1995, the air pollution resulting from fuel combustion is 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 (World Bank 1997). The primary culprit is believed to have been fine PM.

Of course, much of the adverse health impacts of urban air pollution manifest themselves through diseases such as lung cancer, cardiovascular and respiratory conditions including infections. The World Health Organization (2002) estimated that urban PM accounts for about 5 percent of trachea, bronchus, and lung cancer cases, 2 percent of deaths from cardio-respiratory conditions, and 1 percent of respiratory infections. Worldwide this amounts to about 0.8 million deaths annually, and the burden occurs primarily in developing countries (WHO 2002).

While some developing countries still monitor only TSP, a growing number of urban centers are focusing on finer fractions—PM_{10}, $PM_{2.5}$, and/or $PM_{0.1}$. This shift is important because of the association of fine particles with more damaging health effects. Also, the shift allows a better understanding of the environmental fate of the particulates being studied (e.g., the finer particles' ability to be transported long distances because they remain in the atmosphere longer).

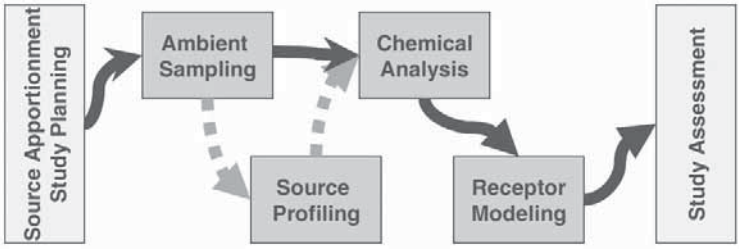
The adverse impacts of PM pollution extend beyond the direct health impacts discussed above. For example, air pollution particles scatter and absorb solar radiation depending on their chemical composition or refractive index resulting in direct contributions to climate change by reducing ground-level solar radiation. The so-called aerosol indirect effect is the change in cloud properties resulting from the excessive number of airborne particles. This effect can potentially change the hydrological cycle, impacting rain patterns. Particulate pollution can also impact visibility (i.e., via haze or smog), damage buildings, and destroy vegetation.

Top-Down Source Apportionment of Emissions

Top-down source apportionment methods are useful in gaining scientific understanding of a city's air pollution problem. In particular, top-down methods can quantify the relative contributions of different sources to the overall PM problem. Because these methods can be applied relatively quickly and inexpensively, they are particularly relevant for application in developing country cities.

Source apportionment methods are based on the fact that different emission sources have characteristic chemical patterns or profiles of air pollution. For example, iron and steel mills emit PM that is rich in iron, cement plants emit PM containing calcium, and diesel exhaust contains largely carbonaceous PM. In general, specific elements, such as metals can serve as tracers of pollution from different industrial processes. Source apportionment aims to explain the chemical composition of ambient PM samples as a combination of contributions from different sources. In doing so, source apportionment quantifies the relative contributions of these different sources. Figure 1 presents the steps needed to perform a top-down source apportionment or receptor study.

Figure 1 Steps Required to Perform a Top-down Source Apportionment Study



Source: Authors' calculations.

Ambient samples are collected in locations of interest in an urban region, and these samples are analyzed for their chemical composition. Profiles of the composition of different sources can also be analyzed, or source profiles can be used from other urban areas. Quantitative methods or receptor modeling are then used to estimate the relative contributions of different sources to the total PM measured in the first step. A successful study therefore requires careful planning, appropriate air sampling and analytical equipment, and an appropriate level of technical competence to complete the necessary steps and draw appropriate conclusions.

A receptor-based source apportionment study provides:

i. information on the types of sources responsible for the observed pollutants,
ii. estimates of the percentage contribution of the sources for different locations during a given time period, and
iii. a basis for evaluating realistic and cost-effective strategies to reduce PM pollution.

Because top-down methods are based on ambient data, the first steps in a successful PM sampling program are selection of sampling sites, selection of a suitable sampler and size range, and selection of filter media amenable to the desired physical and chemical analyses. The sampling sites need to represent an urban area's zones (e.g., residential, industrial, roads, commercial, parks, sources, background) and be representative of population impacts. The number of samples should be sufficient to represent the range of meteorological and emissions conditions. A properly formulated conceptual model reduces the cost and time of source apportionment by facilitating selection of: monitoring locations well suited for the tasks at hand; the size range of particles to be monitored; the species to be analyzed in ambient PM; and the number of samples to be taken and analyzed.

A key component needed to conduct a top-down analysis is a collection of source profiles reflective of the emission sources impacting the urban area being studied. A source profile identifies the quantities of specific air pollutants (elements and ions) emitted from individual sources. These profiles are pivotal in estimating the contribution of various pollution sources to ambient concentrations. The more accurate a source profile, the more likely that quality results will follow. Source profiles can be obtained locally, but most of the source profiles currently available are from industrial countries, where the mix of fuels used and combustion technologies employed may be different from those utilized in developing countries. Some studies are underway to determine source profiles for developing countries, but this avenue of research is still in its infancy. The dotted arrows in Figure 1 indicate that a customized source profile (the ideal situation) can be developed for a particular urban area or source profiles can be utilized from other studies of areas with similar source characteristics.

Source profiles may consist of a wide range of chemical components, including elements, ions, carbon fractions, organic compounds,

isotopic abundances, particle size distributions and shapes. In top-down analysis, whatever is measured at the source must also be measured at the receptor, and vice versa. Source markers are sought that are abundant in one type of source, but are minimally present in other source types. These markers must also have relatively stable ratios with respect to other components in the source profile. For example, biomass burning has a strong signal in potassium (K), while dust contains aluminum (Al) and silicon (Si). Carbonaceous materials measured along with elements include: (1) organic, elemental (light absorbing or black carbon), and carbonate; (2) thermal carbon fractions that evolve from PM at different temperatures; and (3) specific compounds present in the organic carbon fraction.

Organic marker compounds have become more useful as many toxic elements formally used as markers are removed from emission sources (e.g., lead from gasoline engine exhaust). Analysis using organic marker compounds can be quite useful when identifying contributions of sources that emit primarily carbonaceous particles. For example, this type of analysis can distinguish between diesel and gasoline exhaust (see Figure A3.4) and between soil dust and road dust. Organic compounds are also useful in distinguishing emissions from ethanol fueled versus gasoline fueled vehicles. Studying the organic component of sources is also important because this complex mixture of organic compounds, many of which can cause cancer and genetic mutations, makes up approximately 30 to 50 percent of the $PM_{2.5}$ in urban environments. By utilizing modern extraction methods, organic compounds can be measured at costs comparable to those for elements, ions, and carbon.

Physical and chemical analyses of the characteristic features of particulate matter include shape and color, particle size distribution (number), and chemical compounds. Temporal and spatial variation of these properties at receptors also helps to assign pollution levels to source types. Although most of these features can be used to identify source types, the only measures that can be used to determine quantitatively a source contribution to ambient PM levels are component concentrations described in the source profiles.

Several different technologies and methods exist for sampling atmospheric PM, analyzing its chemical composition, and performing receptor modeling. Each system has its strengths and weaknesses. A chosen system needs to be matched with the anticipated needs of an urban air source apportionment study. For example, if biomass burning is suspected to be a major problem area for a particular urban area, a system strong in detecting biomass burning tracers needs to be selected. Source apportionment study planning (Figure 1) plays a critical role in system selection. The analytical measurements should be selected based on the resources available for the study, species to be measured and the types and number of ambient samples to be collected. It is again noted that the sampling and analysis should be planned together as certain analytical measurements cannot be performed unless the samples have been collected in a specific way using a specific filter.

Advantages of source apportionment are that it:

i. determines if selected monitoring sites or hot spots exceed compliance levels;
ii. identifies critical pollutants of concern;
iii. may differentiate the chemical composition of PM (e.g., the primary and secondary contributions);
iv. describes source impact estimates;
v. identifies sources which would be most effective to control; and
vi. avoids the uncertainties associated with the emission inventories and meteorological inputs required for the bottom-up approach.

Limitations of source apportionment include:

i. the need to have and apply appropriate source profiles which match emission sources with ambient air pollution;

ii. in some cases not being able to differentiate sources that have similar chemical composition (known as collinear), for example, cooking and open burning, or resuspended road dust and soil dust; and
iii. not being able to fully account for possible nonlinearities due to chemistry and the formation of secondary aerosols.

Source Apportionment Case Studies in Developing Countries

To illustrate the techniques described in this report, thirteen source apportionment case studies conducted in developing country urban areas are described in Chapter 4 (Table 1).[1] The cases described in the report 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.

Two of the studies, Santiago and Sao Paulo, focused on PM_{10}. The other studies concentrated on fine particulate matter ($PM_{2.5}$). 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. Additionally, there are no specific emission factors established that can be applied to all the urban areas. However, by providing information on the proportion of dust in a measured sample, top-down source apportionment methods can provide an estimate of the contribution dust emissions make to air pollution at the receptor sites.

In addition to the studies summarized in Table 1, this report presents results of an in-depth analysis conducted in Hyderabad, India (which is the fifth largest city in India).[2] The study began with development of a bottom-up emission inventory. The results of the emission inventory and subsequent air quality modeling indicated that the primary source of PM_{10} emissions in

Table 1 Fifteen Urban Area Case Studies Utilizing the Techniques Described in This Report

Regions	Urban Areas
East Asia and Pacific (EAP)	Shanghai, Beijing, Xi'an, Bangkok, Hanoi
South Asia Region (SAR)	Mumbai, Delhi, Kolkata, Chandigarh, Dhaka and Rajshahi
Africa	Cairo, Qalabotjha, Addis Ababa
Latin America and Caribbean (LAC)	Sao Paulo, Mexico City, Santiago

Source: Authors' calculations.

[1] In addition, many other receptor model studies are referenced in the bibliography.

[2] See Chapter 5 for details of this study.

Hyderabad is the transportation sector (~62 percent) with the industrial sector being the second largest source of PM_{10}. The subsequent top-down study utilized three monitoring sites and found that for PM_{10} the average contribution of mobile sources (petrol, CNG, and diesel) ranged from 49.2 percent to 58 percent. For $PM_{2.5}$ mobile sources contributed 49.4 percent to 56.0 percent making it the dominant PM source in the region.

The Hyderabad study was intended to create a more comprehensive approach to the region's air pollution challenges. The receptor-based, source apportionment modeling complemented the emission inventory phase of the study to improve the overall quality of the air pollution information available to regulators and policymakers. One of the most significant challenges of the receptor-based study was the lack of local source profiles for the Hyderabad area. A composite of profiles from other similar areas was utilized, and these profiles were selected from a data base in such a way as to yield reasonable statistics for the collection sites utilized in the study. While an acceptable practice, it is clearly preferable to generate customized profiles specific to the region. At least some of the most important and critical profiles should be obtained locally including local soil dust, vehicle profiles, and major industries in the region.

Policy Implications

Policymakers in rapidly growing urban areas increasingly recognize that addressing air quality issues is an urgent priority but often lack sufficient information on the sources of air pollution and must compete for resources with other high-priority concerns. Receptor-based source apportionment techniques, coupled with bottom-up analysis, can supply reliable, science-based information on pollution sources for air quality management. In the past, bottom-up analyses have overestimated some pollution sources while missing entirely other important contributors. Without properly identifying the sources of pollution it is difficult for policymakers to formulate rational, effective policies and make informed investment decisions related to air quality improvements.

Top-down source apportionment can provide meaningful information on the relative contributions of different sources, in places where little is known about the local air pollution problem, and the initial investigations can be conducted with relatively little effort, and at relatively low cost. That is, top-down source apportionment can begin modestly and evolve in its level of sophistication, usefulness, and cost. Consequently, these methods are particularly relevant for developing nations. They can subsequently be improved by collecting more ambient samples, and by using more sophisticated methods of analysis. Likewise, in locations where emission information is more extensive but based on bottom-up methods, top-down source apportionment provides an important test for the accuracy of the bottom up results.

Fortunately, bottom-up and top-down analyses are not all or nothing activities. That is, attaining effective air quality management systems can be viewed as a process of growth from relatively elementary systems utilizing relatively simple analytical techniques to effective systems utilizing sophisticated ones. Developing country cities that have not previously developed an AQMS can begin with top-down assessments, while cities with more experience can augment existing systems and include receptor based modeling. The accumulated knowledge from the growing body of bottom-up and top-down analyses allows air quality managers to improve their AQMS more quickly than in the past. Developing country policymakers can thus make use of traditional bottom-up approaches as well as newer top-down methods to better identify and quantify air pollution sources, which is a fundamental first step in effectively addressing growing air pollution problems.

1 Introduction

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. This segment of the world's population reached 2.9 billion in 2000 and is expected to rise to 5 billion by 2030. Growing levels of urbanization in developing countries have generally resulted in increasing air pollution due to higher activity in the transportation, energy, and 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. As an example of the health impacts, The World Health Organization (2002) estimated that urban air pollution from particles suspended in the air or particulate matter (PM) accounts for about 5 percent of trachea, bronchus, and lung cancer cases, 2 percent of deaths from cardio-respiratory conditions, and 1 percent of respiratory infections. This amounts to about 0.8 million deaths annually, and the burden occurs primarily in developing countries (WHO, 2002).

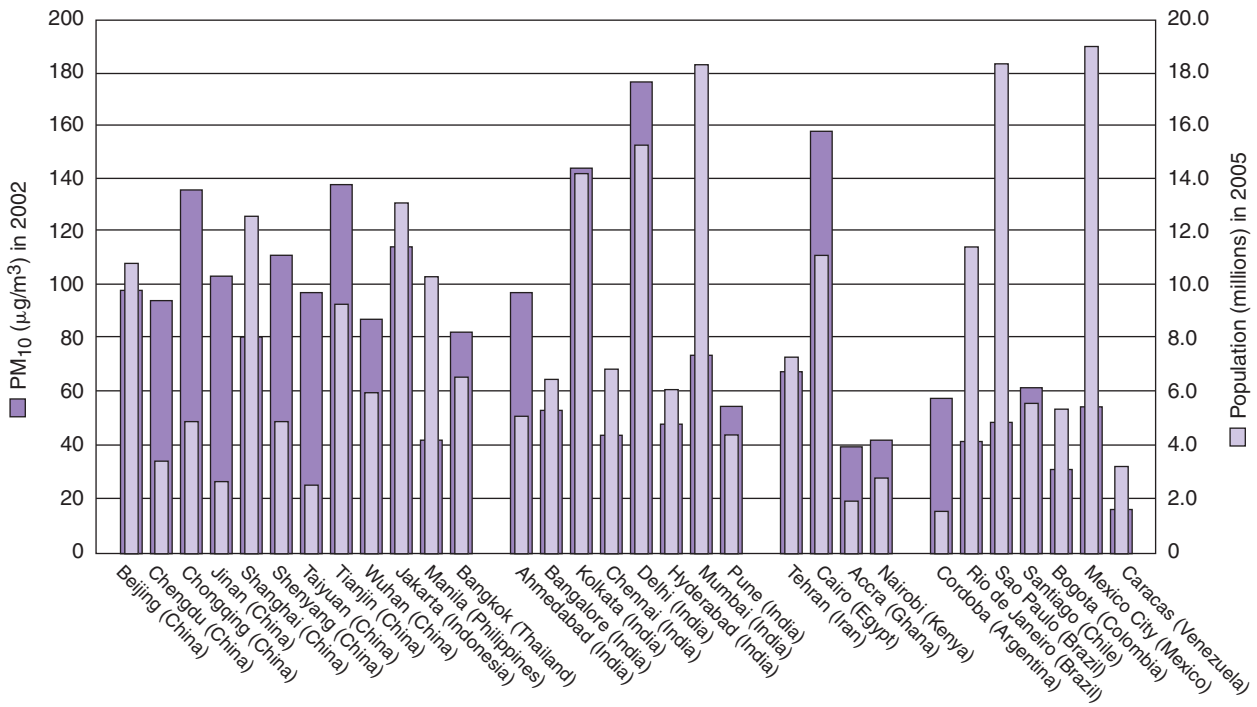
These impacts are particularly severe in developing country mega cities (cities with a population of more than 10 million).[3] Fortunately, major advances have been made in techniques utilized to estimate ambient air pollution levels and identify emission sources, which can augment other techniques normally found in air quality management systems. These advances offer the opportunity for developing countries to implement sophisticated air quality management programs earlier in their development process than was accomplished by their industrial country counterparts. These techniques also offer the possibility of identifying major pollution sources in a cost effective manner. Without these techniques policymakers may guess what the major sources are, but experience has shown that such guesses are oftentimes incorrect, and setting air pollution control policies based on incorrect information can be very costly for an urban area's economy.

In a tangible move toward incorporating these improved techniques into their air quality management systems, many developing countries have shifted their air monitoring programs away from just measuring particulate matter (PM) as total suspended particulates (TSP) toward measurement of inhalable particulate matter (PM_{10}), which is less than 10 μm in diameter, and the subset of fine particulate matter ($PM_{2.5}$).[4] Fine PM has been shown to have more serious health impacts than larger PM (Pope and Dockery, 2006). However, in many cases there is often major disagreement over emission sources, composition, and how emissions can be controlled. Working effectively through these challenges requires sound, scientifically-grounded information on the level, source and composition of air pollution generally and fine PM specifically. This report explores techniques available to allow developing countries to generate this critical information. These techniques look beyond the sources that are easily visible and often miscalculated, such as power plants or vehicles, to include other sources (e.g., trash incineration) that can also make large contributions but whose identification is not always straightforward.

[3] For critical reviews and discussions of environmental impacts in mega cities see Molina and Molina (2004) and Chow, et al. (2004).

[4] Chapter 2 provides detailed information on particulate matter with emphasis on the smaller particles that are readily inhalable.

Figure 1.1 Particulate Pollution in the World's Most Polluted Urban Areas



Source: World Development Indicators 2006, The World Bank.

Objectives and Approach

This review arises from a concern over the lack of information on the contributions of specific source categories of air pollution—especially for fine mode particulate matter ($PM_{2.5}$). Without understanding the sources of pollution, it is difficult for policymakers to formulate rational, effective policies and make informed investment decisions related to air quality improvements. This also raises the need for cost-effective, accurate ways of determining the principal sources of fine PM.

The main objectives of this study are to review, demonstrate, and evaluate methods to assess and monitor the sources of PM, using a combination of ground-based monitoring and source apportionment techniques referred to as top-down or receptor-based methods. As a supplement to existing efforts to quantify air pollution, these methods have the potential to be particularly useful within the context of urban areas located in developing countries. This is the case because: (1) PM concentrations can be high in developing countries, necessitating action to protect health, and (2) in developing countries emission factors are generally less well known than in industrial countries making it more difficult to infer major sources from emission inventories associated with bottom-up methods, the other approach available to quantify air pollution (described below). Top-down methods offer the promise of providing a quantitative assessment of the relative contributions of different sources to ambient air pollution, where rather little may be currently known. Additionally, top-down methods may require few atmospheric measurements and relatively simple analysis. However, it must be stressed that top-down source apportionment should be viewed as supplementing currently utilized bottom-up methods and not replacing them.

The implementation of this project will involve four general tasks:

- Review of the science of source apportionment techniques (e.g., monitoring, filters, analysis,

and modeling techniques)—in the combined use of monitoring data and modeling for better understanding of the relative contributions of different sources to the observed PM;
- Review of recent top-down applications from developing countries (e.g., equipment used, methods employed, and results);
- Demonstrate the feasibility of the chosen methodology through a pilot project; and
- Evaluate source apportionment techniques for cost-effective application in developing nations.

Because of the importance of PM pollution for human health, visibility, climate, and the environment, this report focuses on this type of pollution, while attempting to remain general enough to be applicable to a wider range of pollutants.

The ultimate objectives of this project are to: provide a guide to environmental institutions in practical methods of source apportionment (i.e., top-down methods), communicate to policymakers the advantages of top-down methods and how they can be used effectively, in combination with bottom-up techniques, as part of an air quality management system (AQMS), and disseminate broadly the findings and conclusions within the scientific and local/national environmental communities.

Nature of the Problem

Fossil fuel combustion (e.g., combustion for domestic cooking and heating, power generation, industrial processes, and motor vehicles) is typically a major source of air pollution in developing country cities. In addition, the burning of biomass such as firewood, agricultural and animal waste contributes a large proportion of the pollution in some urban areas, and these traditional sources are often neglected (and difficult to estimate) through bottom-up emission inventories. Important pollutants include particulate matter (PM), sulfur dioxide (SO_2), volatile organic compounds (VOCs), lead (Pb), carbon monoxide (CO), nitrogen oxides (NO_x), ammonia (NH_3), and ozone (O_3) (an important secondary pollutant formed due to the chemical interaction of the various pollutants mentioned above). Urban air pollution not only has immediate localized impacts on human health and well being but also contributes to regional and global air pollution. Emissions of greenhouse gases (GHGs) resulting from the combustion of fossil fuels in the industrial and transportation sectors contribute to global climate change and is estimated to grow significantly in developing country cities. So, policies to improve urban air quality can be beneficial to global climate change issues. For instance, improving the design of urban transportation can improve local air quality while reducing carbon dioxide emissions.

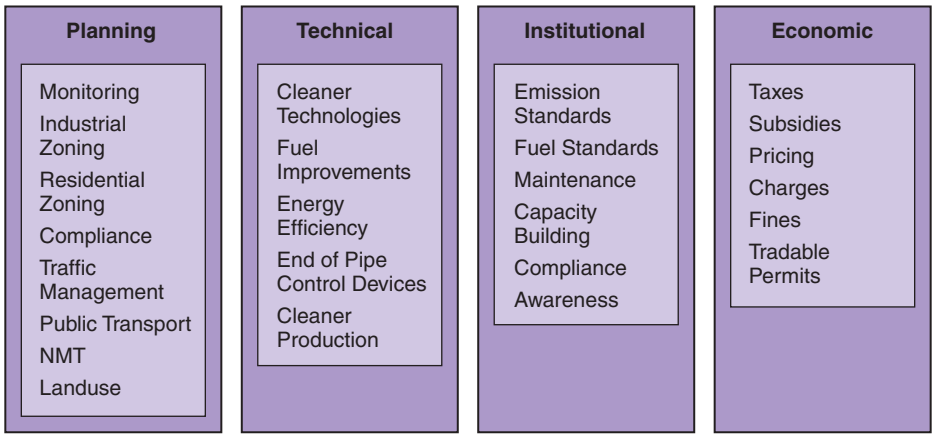
Past and present research activities in industrialized and developing countries have helped to improve the understanding of the impacts of air pollution on human health and the environment. Of all the pollutants listed above, most of which are regulated through established ambient air quality standards,[5] it has been shown that particulate matter (PM) is one of the most critical pollutants responsible for the largest health and economic damages. The World Health Organization's Global Burden of Disease study found that exposure to PM has wide ranging impacts on health with its substantial link to mortality as the most important impact (Cohen et al., 2004). Further, in a U.S.-based study, Pope et al. (2002) established a link between long-term exposure to fine PM and lung cancer and cardiopulmonary mortality. In several developing cities like Sao Paulo and Santiago de Chile, high PM levels were clearly associated with increases in infant and elderly mortality.

What Is the Best Way to Reduce Air Pollution in a Particular Urban Area?

This is a question often asked by city managers who are confronted with a wide-ranging and often confusing choice of possible measures (see

[5] WHO, 2006 Air Quality Guidelines—http://www.who.int/phe/health_topics/outdoorair_aqg/en/

Figure 1.2 A Typology of Measures for Managing Air Quality



Source: Authors' calculations.

Note: NMT = Non-motorized transport.

Figure 1.2) that could be used in innumerable combinations. These measures include policy, technical, economic, and institutional options, and they can be formulated as the more traditional command-and-control or contain market-oriented aspects. For a recent summary of these air quality management issues see Bachmann 2007.

Before one can answer the above question, one needs to ask, *what are the contributing sources of air pollution and how will their excessive levels respond to direct emission reductions?* Currently, developing countries often focus on the transportation sector as the main contributor to increasing air pollution problems. Even if this sector is a major contributor, there are many subsets within the transportation category, including engine types (two-stroke gasoline, four-stroke gasoline, diesel), vehicle sizes and functions (buses, trucks, taxis, two-wheelers, three-wheelers, trains, ships), vehicle age, maintenance, and operating conditions (cold start, stop-and-go) that may need to be addressed to achieve meaningful emission reductions. However, other important sources may include fossil fuel (oil and coal) combustion in electric power generating stations, factories, office buildings, and homes. Additional sources that may not be fully quantified include the incineration of trash or biomass burning (including transported from elsewhere).

Given a variety of emission sources in an urban area, the options listed in Figure 1.2 need to be analyzed not only from an environmental, social and economic viewpoint, but also with respect to public and political acceptability, ease of implementation, and, of course, cost. It is essential that any framework utilized to analyze these options takes all of these considerations into account. The aim is not only achieving technical feasibility (to see if environmental goals can be achieved) or economic prudence (to ensure that a cost effective approach is utilized) but also social acceptability (especially for options that involve behavioral change or sacrifices).

Amassing an accurate knowledge base for air quality management is critical and often a constraint in developing countries. Compiling such a knowledge base necessitates developing an understanding of the critical pollutants, their sources, and possible control options. Once this is accomplished it is necessary to develop simple tools to analyze options in an integrated manner, conduct more detailed studies and develop methodologies as required and eventually prioritize a feasible set of options that can be implemented. Timing is important because many cities in developing countries are growing rapidly and planning air quality management systems in advance will help avoid the potentially serious health problems that can

arise if air pollution is allowed to reach a crisis level before action is taken.

In order to conduct a full-scale analysis of air pollution sources, there are a number of problems city governments from developing countries have to overcome.[6] These include:

- Existing full-scale methodologies may involve large data collection efforts that may be beyond the technical and financial means of some countries. However, as pointed out later in the report, countries do not have to begin their air quality management programs with full-scale analyses. It is possible to begin with simple, relatively inexpensive, yet useful analyses and progress into full-scale analyses. For examples of preliminary analyses see Sharma, et al. (2003) and Etyemezian, et al. (2005).
- Developing country environmental agencies are often weak and understaffed, with inadequate skills, capacity, and funding.
- Institutional problems are common in developing countries (import restrictions and bureaucracies often do not facilitate movement of people, know-how, and technical equipment across borders).
- Emission inventories and databases are often difficult to access and are not of the required quality and consistency.

In spite of these limitations, there are many examples of successful PM measurement and source apportionment studies in a wide variety of developing countries, as described in this report and documented in citations in the bibliography.

Top-down versus Bottom-up Modeling of Source Apportionment—Preview

There are two fundamental and complementary approaches to determining the source of air pollution: (1) top-down or receptor-based source apportionment (the focus of this report); and (2) bottom-up or source-based. Both approaches should be utilized in an effective air quality management system. The top-down approach begins by sampling air in a given area (i.e., via air sample receptors) and inferring the likely sources from common characteristics among source and receptor concentrations. Bottom-up models begin by identifying sources and their emission factors. This information is then combined with meteorological patterns to predict pollution levels and compositions. Ideally, the two approaches should agree, but this is rarely the case for an initial application. However, identifying a disagreement allows for improving both methods, and acceptable agreement is often achieved after several iterations. This adds confidence to the selection of control strategies. Chapter two covers these approaches in detail presenting strengths and weaknesses of each. However, the main focus of this study is the top-down approach, since it provides relatively cost-effective ways for developing nations to learn about the sources of their urban air pollution. In particular, the study will illustrate the techniques used in top-down modeling and how the top-down approach can help developing countries overcome the problems listed above. However, the top-down approach should not be viewed as a replacement to bottom-up techniques. Ideally, the two reinforce each other and result in a higher quality air quality management system.

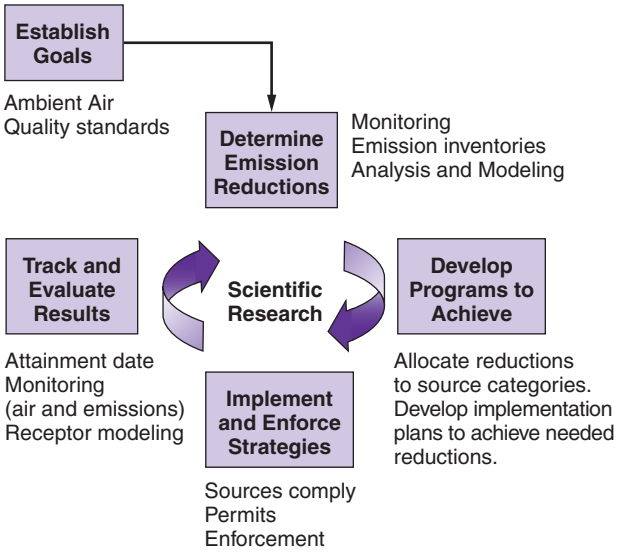
Top-down and Bottom-up Modeling—Their Place in an Air Quality Management System

Figure 1.3 presents a graphical representation of air quality management (AQM) theory. This representation is often referred to as the AQM "wheel" or "circle" (Bachmann 2007).

The AQM wheel is intended to capture the dynamic nature of air quality management systems. At the heart of the wheel is scientific research, and as more is learned about the complex nature of air pollution through research, changes need to be made in the AQMS. These advancements can come in the form of

[6] It should be pointed out that developed countries face many of these same problems.

Figure 1.3 Air Quality Management Theory



Source: Bachmann (2007).

improved knowledge about how air pollution impacts health and the environment, or in the technology used to monitor air pollution and apportion it to emission sources, or in how to best achieve needed reductions. As a result of these advancements, standards, monitoring methods, and enforcement practices need frequent review and revision (i.e., improvement). Nonetheless, because our information is never complete, policymakers are always faced with a judgment as to how strict to make standards. This puts air quality management systems into the category of "risk-based" environmental programs. Because of the risk that standards may be inappropriate, groups required to reduce pollution emissions as a result of the standards have a basis to complain. Hence these groups may pressure policymakers to loosen the standards. At the same time other segments of the population may believe the risk is greater than policymakers determined, and as a result may pressure for stricter standards.

The above impacts on the AQMS can be viewed as coming from outside a particular system. That is, the scientific research discussed in the previous paragraph applies to air quality management generally and not a specific AQMS. However, continuous scientific research within the AQMS is needed to improve the quality of the system's results. Specifically, because of the complex nature of determining the level, nature, and source of air pollution, there is always room to improve an AQMS. Additionally because urban areas are continually changing, the pollution sources and levels as well as responsible parties are continually changing. One way to improve the quality of the AQMS and cope with the dynamic nature of the problem is to improve the quality of the basic building blocks of the system. For example, developing a quality inventory of potential air pollution sources and their likely emissions (a bottom-up activity) is an expensive, time consuming, difficult, yet essential task for allocating emission reductions to individual polluters. An emission inventory has to be updated continually to reflect ever-changing emission sources. For example, new manufacturing plants may open in an urban area requiring the inventory to be updated, and emissions at existing plants may increase or decrease. Additionally, emissions from a particular source likely vary as operating conditions change (e.g., as operational efficiencies change), and because of potential enforcement activity if standards are not met it is not in the interest of management to be open about what might be considered excessive air pollution emissions. As a result, no emission inventory is completely accurate. Analyzing ambient air pollution and identifying sources through top-down source apportionment techniques can help uncover weaknesses in emission inventories. The result is an improvement in the AQMS. Concurrently, improvements in emission inventories may point out weaknesses in top-down activities leading to improved source apportionment in subsequent rounds of analysis. The result is a process of continual improvement through scientific research from within the AQMS. A fortunate side effect of this dynamic process for cities in developing countries is that air quality management systems can begin small with relatively low cost and improve step-by-step. This report will emphasize this hierarchy of top-down source apportionment methods, which when coupled with bottom-up methods allow for continual improvement.

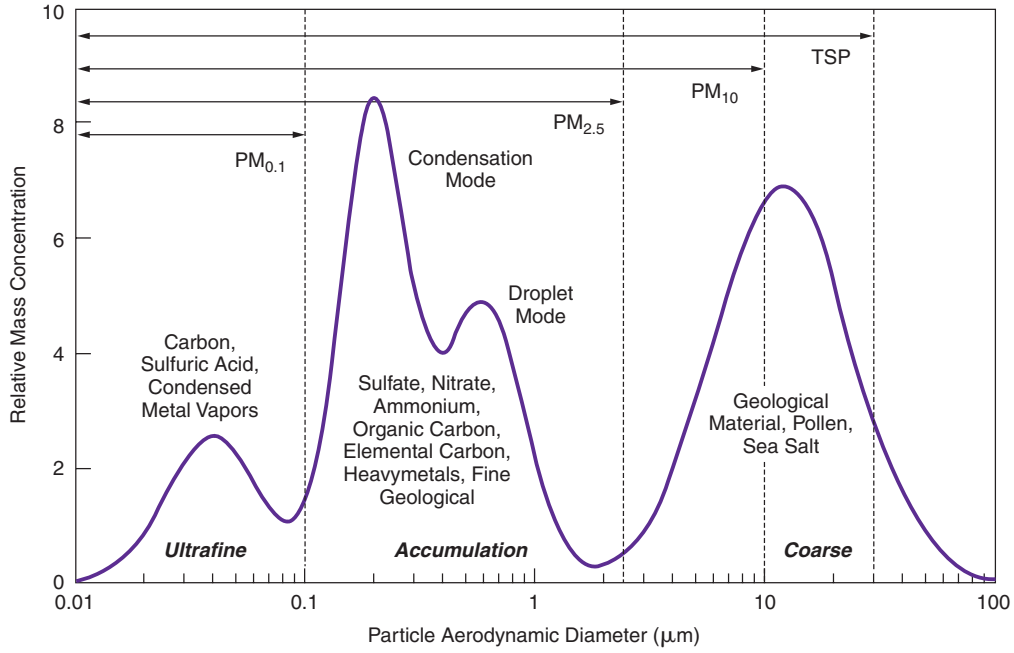
2 Particulate Matter and Apportionment

What Is Particulate Matter?

Particles suspended in the air are classified by size (aerodynamic diameter) and chemical composition, and are often referred to as particulate matter (PM) or aerosols. Airborne particles are classified by size into coarse, fine, and ultrafine particles (Figure 2.1). 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), and $PM_{2.5}$ (with an aerodynamic diameter of less than 2.5 μm, also referred to as fine), and ultrafine particles are those with a diameter of less than 0.1 microns (see Figure 2.1). 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.

A comparison of the properties of fine and coarse mode particles is given in Table 2.1. 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. Averaged over the globe, aerosols resulting from human activities

Figure 2.1 Particle Size Distribution



Source: Judith Chow, Desert Research Institute, USA. Chow, J.C. (1995).

Table 2.1 Comparison of Ambient Fine and Coarse Mode Particles

	Fine Mode (PM2.5)	Coarse Mode (PM10)
Formed from	Non-combustibles in fuels (ash), incompletely combusted fuels, gas-to-particle conversion in the atmosphere, extensive grinding of coarse material, nucleation of condensable gases.	Ground minerals, pollens, spores, plant parts, sea salt.
Formed by	• Chemical reactions. • Nucleation, condensation on nuclei and coagulation. • Evaporation of fog and cloud droplets in which gases have dissolved and reacted.	• Mechanical disruption (grinding, crushing, abrasion of surfaces, etc.) • Suspension of dusts.
Composed of	• Sulfate, nitrate, and ammonium ions. • Elemental carbon. • Organic compounds (e.g., polyaromatic hydrocarbons). • Metals (e.g., lead, cadmium, vanadium, nickel, copper, zinc, manganese, iron).	• Resuspended dust (soil dust, street dust). • Coal and oil fly ash. • Oxides of crustal elements (silicon, aluminum, titanium and iron). • $CaCO_3$, NaCl, sea salt. • Pollen, mold, fungal spores. • Plant/animal fragments. • Tire-wear debris.
Solubility	Sulfates and nitrates are soluble, hygroscopic, and deliquescent.	Largely insoluble and non-hygroscopic.
Sources	• Combustion of coal, oil, gasoline, diesel fuel and wood. • Atmospheric transformation products of nitrogen oxides, SO_2 and organic compounds, including biogenic organic species (e.g., terpenes). • High-temperature processes, smelters, steel mills, etc.	• Resuspension of industrial dusts and soil tracked onto roads and streets. • Suspension from disturbed soil (e.g., farming, mining, unpaved roads). • Biological sources. • Construction and demolition. • Coal and oil combustion. • Ocean spray.
Atmospheric half-life	Days to weeks.	**Minutes to hours**
Travel distance	100s to 1000s of km.	**Typically < 1 to 10s of km (Asian and Saharan dust may travel 1000s of km, although the size distribution does shift toward smaller particles as the distance grows).**

Source: Authors' calculations.

currently account for about 10 percent of the total. Most of that 10 percent is concentrated in the Northern Hemisphere, especially downwind of industrial sites, slash-and-burn agricultural regions, and overgrazed grasslands (NASA 1999). The human contribution is far higher when only fine aerosol is considered. For example, anthropogenic inputs are about 70% of sulfur and over 80% of black carbon concentrations.

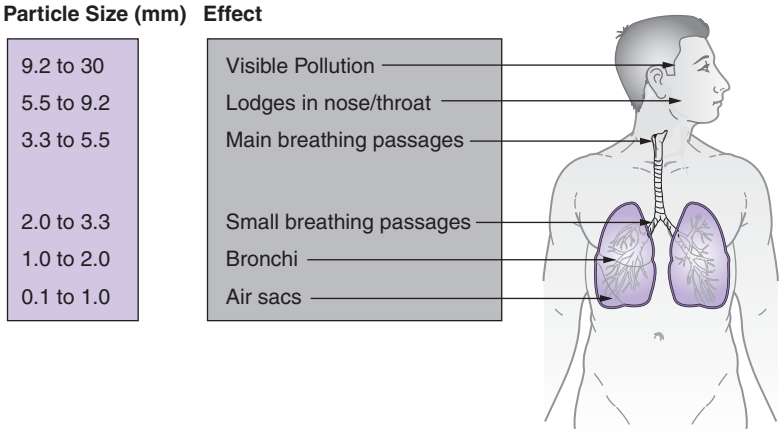
In terms of mechanisms of emissions, particulate matter is classified into two categories, primary and secondary particles. Primary particles are emitted directly into the atmosphere from sources such as burning, industrial activities, road traffic, road dust, sea spray, and windblown soil and are composed of carbon and organic compounds, metals and metal oxides, and ions. Secondary particulates are formed through the chemical transformation of gaseous, primary pollutants such as SO_2, NO_x, certain VOCs, and NH_3 among others.

PM Pollution and 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.[7] 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.

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.[8] 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.

Figure 2.2 Effects of Particulate and Their Size on Human Health



Source: Judith Chow, Desert Research Institute, USA. Chow, J.C. (1995).
Note: Particle size measured in micro meters (μm).

[7] For more information see Health Effects Institute (HEI) (2004).

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

Numerous studies suggest that health effects can occur at PM levels that are at or below permitted national and international air quality standards (e.g., U.S. EPA (2006)). Table 2.2 provides a sense of the range of estimated PM exposure/mortality responses reported in a comprehensive review of recent studies (Pope and Dockery 2006). For short-term exposures Pope and Dockery 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. For long-term exposure (years) there were only two PM_{10} studies reported by Pope and Dockery. These studies are included in Table 2.2. For $PM_{2.5}$, which is more relevant for the source apportionment information being provided in this report, numerous studies were reported by Pope and Dockery, and the lower- and upper-point estimates of mortality increases are presented in Table 2.2 for studies that found statistically significant results. The estimated annual mortality increase from a 10 $\mu g/m^3$ increase in long-term exposure to $PM_{2.5}$ ranged from 6.2% to 17%.

Table 2.2 The Range of Point Estimates of Percentage Increases in All Cause Relative Risk of Mortality Associated with Short- and Long-Term Particulate Exposure

With an Increase in Pollution of	The Estimated Lower-Point Estimate Mortality Increase (Results significant at 95% CI unless noted) (Relevant study)	The Estimated Upper-Point Estimate Mortality Increase (Results significant at 95% CI) (Relevant study)
Relative Risk of Mortality of Short-Term Changes in Exposure (1 to a few days)		
20 $\mu g/m^3$ of PM_{10}	0.4% National Morbidity, Mortality and Air Pollution Study	1.5% Meta-analysis of 29 studies
10 $\mu g/m^3$ of $PM_{2.5}$	0.6% California 9 cities	1.2% U.S. 6 cities
Relative Risk of Mortality Associated with Long-Term Particulate Exposure (Years except as noted)		
20 $\mu g/m^3$ of PM_{10}	2.1% (Not statistically sig. at 95% CI) Adventist Health Study of Smog (> 6000 non-smokers)	8.0% (over months) Post-neonatal infant mortality, U.S.
10 $\mu g/m^3$ of $PM_{2.5}$	6.2% American Cancer Society, extended analysis	17% American Cancer Society Intra-metro Los Angeles

Source: Pope and Dockery (2006).[9]

[9] The Pope and Dockery review article reports on 15 short-term and 25 long-term studies. However, several of the short-term studies were Meta analyses of numerous other studies. Also, several of the studies were variations of other studies (e.g., utilizing an alternate estimation technique, extended time frame, or adjusting for a potential bias). In addition to reporting results dealing with PM_{10} and $PM_{2.5}$ Pope and Dockery also reported studies that generated results for TSP, black smoke, residence near a major road, and a special purpose monitoring of approximately PM_7. See Tables 1 and 2 in Pope and Dockery for details of these studies. Except as noted the results reported here are statistically significant at the 95% confidence level. Pope and Dockery reported other long-term $PM_{2.5}$ results that were not significant at the 95% level.

According to the World Health Organization (WHO) and other organizations, 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.[10]

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,[11] and children living in households using solid fuels have 2–3 times more risk of ARI than unexposed children (Smith, 1999). 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 (Lvovsky 2001). 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.

PM Pollution and Environmental Effects

While health effects drive most of the concern about air quality in developing countries, particulate matter also affects regional and global atmospheric chemistry and the radiation balance. 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 2.3 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. Research continues to assess the effects of many different types of aerosols on climate under different conditions. (Venkataraman, et al., 2005, Andreae, 2001, and Menon et al., 2002).

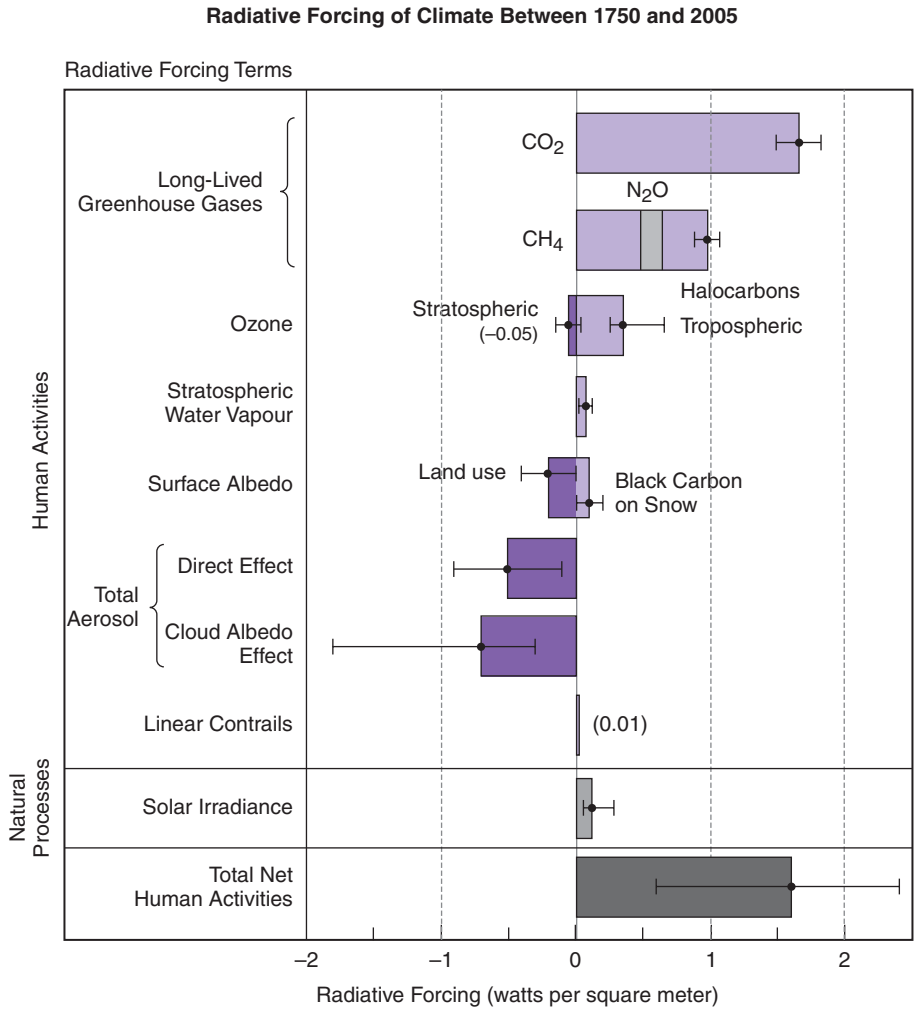
Particulate pollution can also impact visibility in megacities (cities with populations greater than 10 million). Mountains or buildings once in plain sight can suddenly be blocked from view. Air pollution that reduces visibility is often called haze or smog (Watson 2002). The term smog originally meant 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.[12] 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.

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

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

[12] For NASA images illustrating visibility problems see:
Smog in Tehran—http://visibleearth.nasa.gov/view_rec.php?id=20401;
Smog and Fog in India in January, 2006—http://visibleearth.nasa.gov/view_rec.php?id=8330;
Thick Smog over Beijing in November, 2005—http://visibleearth.nasa.gov/view_rec.php?id=17359.

Figure 2.3 Radiative Forcing of Climate between 1750 and 2005[13]



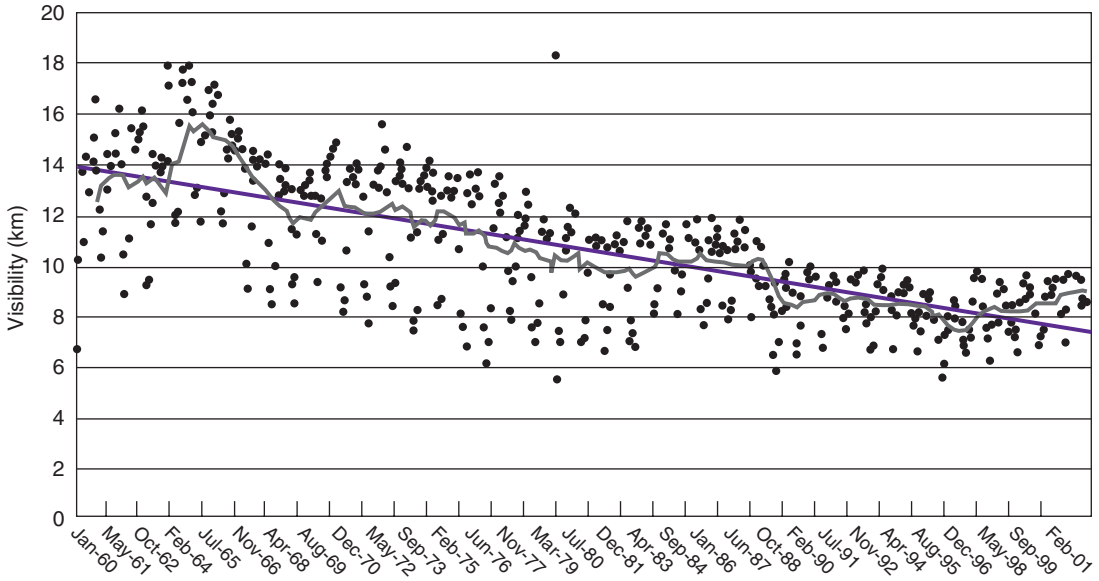
Source: Intergovernmental Panel on Climate Change.

Composition of Particulates

While some countries are still monitoring for total suspended particulates (TSP), a growing number of urban centers are focusing on finer fractions, e.g. PM_{10}, $PM_{2.5}$, and sub-micron PM. Chow (1995) reports that six major components account for nearly all of the PM_{10} mass in most urban areas: (i) geological material (oxides of Al, Si, Ca, Ti, and Fe); (ii) organic matter/carbon (OC—consisting of hundreds of different compounds); (iii) elemental carbon (EC) (also termed black carbon or soot); (iv) sulfate; (v) nitrate; and (vi) ammonium. 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.

[13] Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis, Summary for Policymakers.*

Figure 2.4 Measured Visibility on the Roads of Bangkok[14]



Source: Data from the Pollution Control Department, Bangkok, Thailand.

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 2.3 presents a list of the most commonly detected metals in various emission sources (Chow 1995). 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.

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, volatile organic compounds (VOC) may change into particles; the majority of these transformations result from photochemical reactions that also create high ground ozone levels or smog conditions (Seinfeld and Pandis 1998). Unlike the formation of sulfates and nitrates, for which their 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. For example, fractional aerosol coefficients (i.e., the fraction of the precursor gas that will end up as aerosol after oxidation) were derived by Grosjean and Seinfeld (1989). Although these coefficients are only rough estimates, knowledge can be used to incorporate SOA into source apportionment models and to find cost-effective reduction strategies. In general, SOA (or organic carbon) ranges between 10 to 60 percent of the fine PM depending on the local fuel mix.

[14] Pollution Control Department, Bangkok, Thailand.

Table 2.3 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^+

Source: Chow (2005).

* Marker elements are arranged by priority order.

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.[15] 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.

Sources of PM

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.

The range of particulate 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 air pollution 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 particulate 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.

Major sources of air pollution in urban areas include: combustion processes (e.g., the

[15] 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).

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 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.

In industrial country cities, and 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). 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.

In Africa, PM sources are dominated by biomass burning 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 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.[16] 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 2.5 presents estimated source shares in PM_{10} emission inventories for cities around the world. Totals and information sources are presented in Table A9.1. Also, the long range transport of pollution, especially in neighborhoods downwind of a relatively distant pollution source, makes it difficult to pin point the exact source.

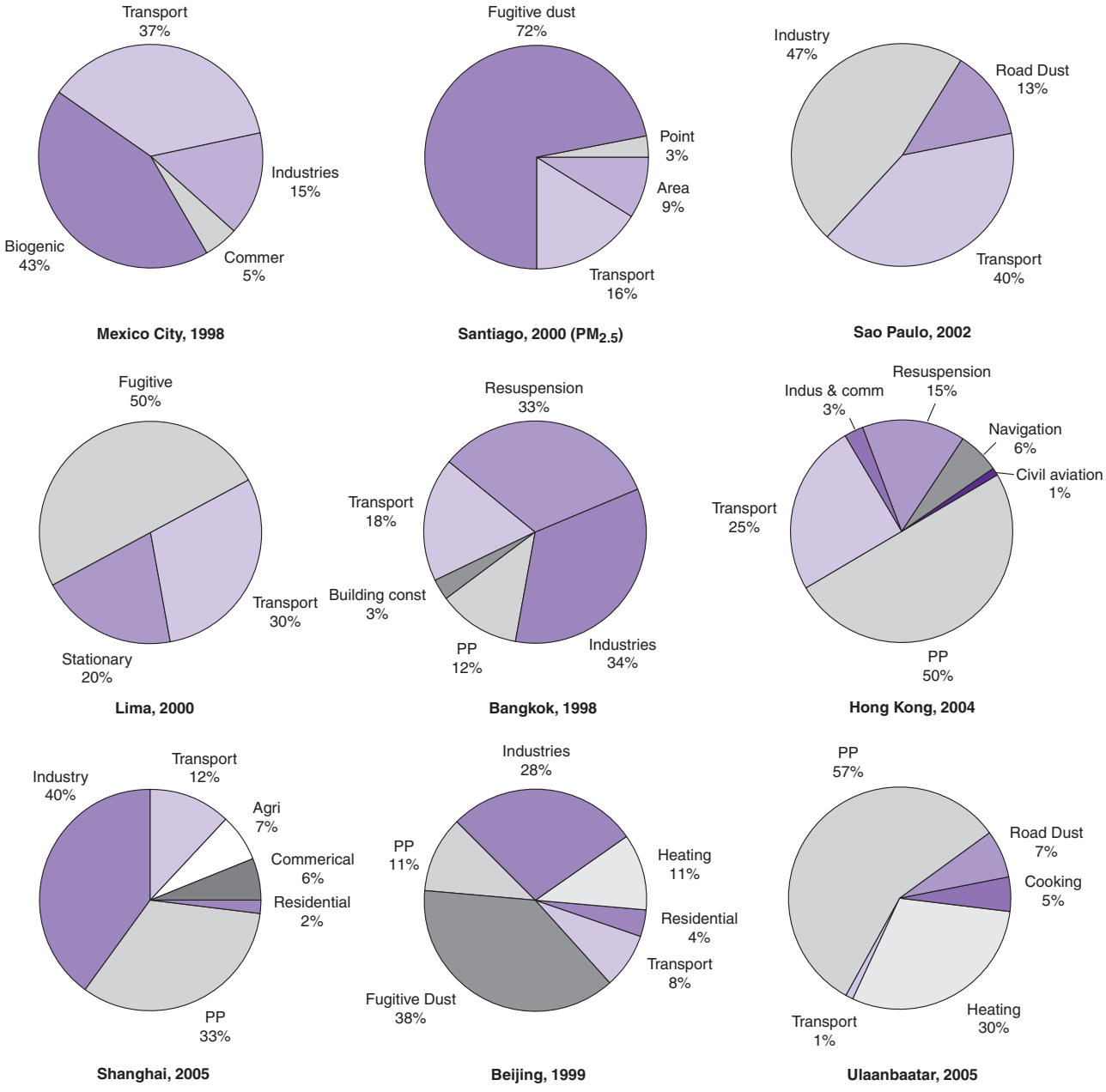
There is no one single dominant pollution source that is common to all the cities listed in Figure 2.5. Direct vehicular emissions and road resuspension accounted for more than 50 percent for Sao Paulo in 2002, compared to 60 percent originating from industries for Greater Mumbai in 2001, and fugitive 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 (Rajbhak et al., 2001). 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.[17]

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 (ESMAP 2005). Unprocessed biomass fuels (wood, dung, and crop residues) and fuels such as coal are common

[16] Fugitive dust is a non-point source air pollution. Significant sources include unpaved roads, crop land, and construction sites.

[17] In Africa, there are some preliminary studies underway to develop emissions inventories for PM and other pollutants, but none are complete and so they are not listed in Figure 2.5.

Figure 2.5 Contribution of Various Sectors to PM_{10} Emission Inventory, estimated using bottom-up inventory methods[18]



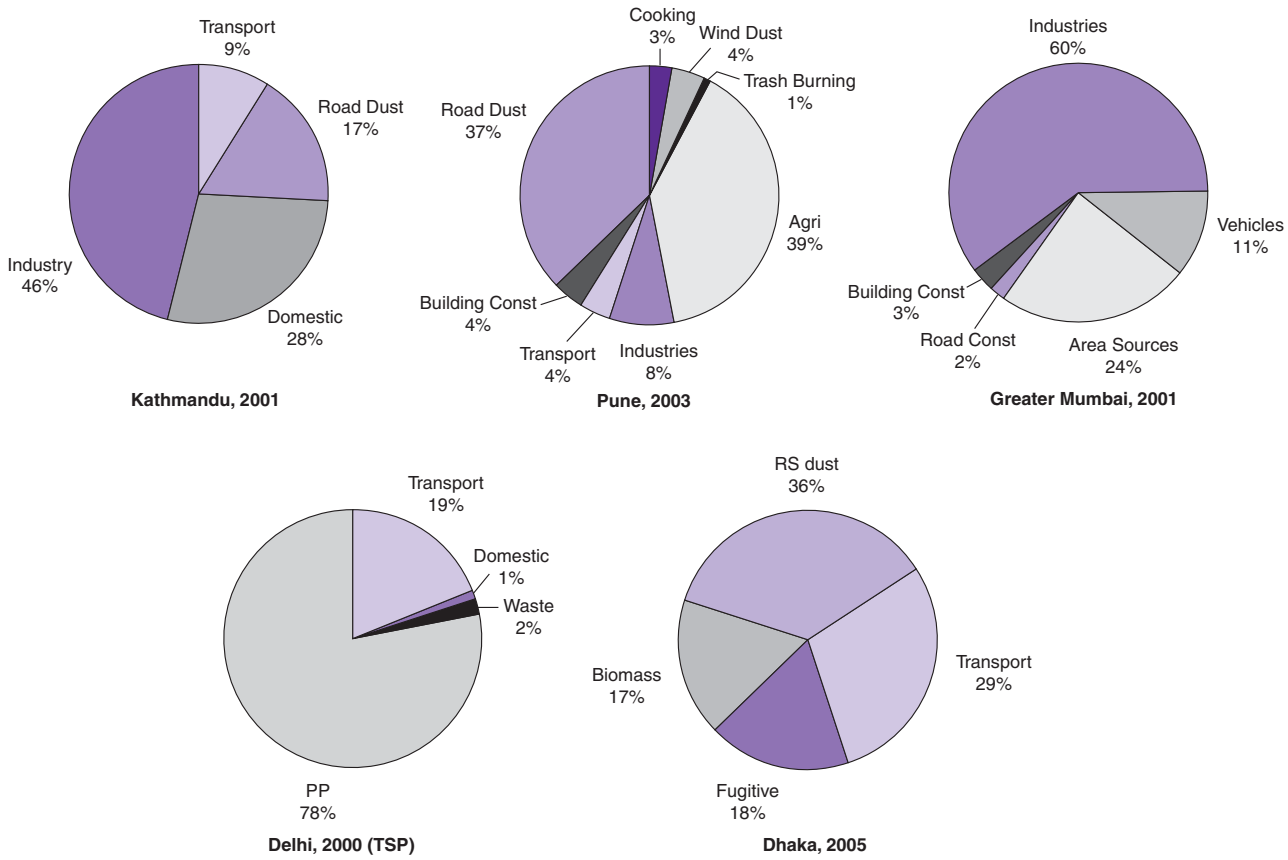
Source: Refer to Table A9.1 for sources.

Note: PP = power plant
RS Dust = resuspended dust

(continued)

[18] References for these studies are listed in Table A9.1. 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 2.5 *continued*

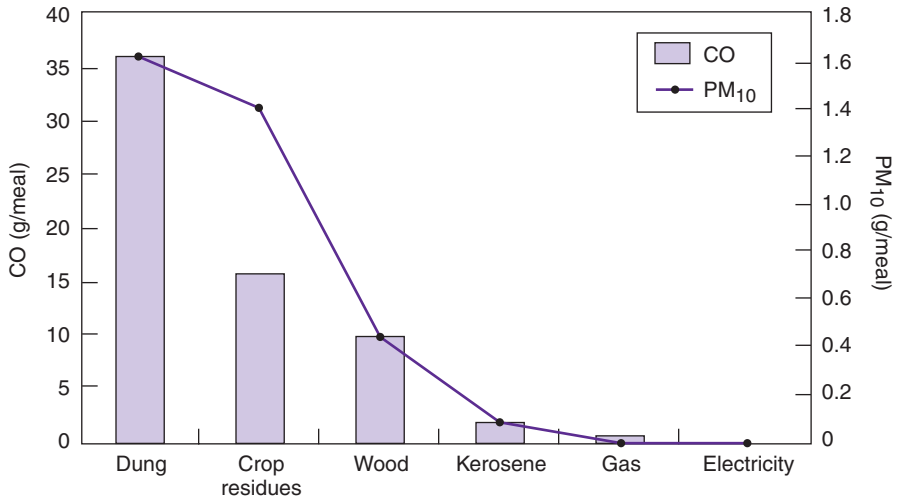


household energy sources in these countries, and they are high emitters of PM and a multitude of other pollutants. In general, these fuels are used in developing countries because of their availability and affordability and are known to emit more carcinogens which tend to worsen rural indoor environments more than urban outdoor environments (WHO 2006). The percent usage of biomass fuels and unprocessed fuels is lower, but not negligible, in urban centers (Streets et al., 1998 and 2003).

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 (Ritchie and Oatman 1983, Keyanpour-Rad 2004, and Cheng, et al., 2001). Africa's fuel 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 (ESMAP, 2002 and Ezzati, et al., 2002). 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 (Kammen 1995). Figure 2.6 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,

Figure 2.6 Emission Rates of CO and PM_{10} by Household Fuel



Source: Practical Action Web Site. http://practicalaction.org/?id=smoke_report_3

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.[19] Further, spring dust blown from the Gobi desert[20] has been detected across the Atlantic Ocean days after passing over the Pacific Ocean and during Northern American transit raising PM levels above World Health Organization (WHO) guidelines (Jaffe et al., 1999). During these dust storm periods, PM measurements of over 1000 $\mu g/m^3$ 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.

Apportionment of Particulate Pollution

In order to set priorities for urban air quality improvements, information is needed on sources and their contribution to the ambient levels of pollution. The purpose of source apportionment

[19] Africa to Atlantic, Dust to Dust—http://www.gsfc.nasa.gov/feature/2004/0116dust.html

[20] 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 6, 2006: http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=13953.

is to reduce the level of uncertainty in the estimates of the contribution sources (e.g., transportation, power, industry, residential, commercial, agricultural, construction, and natural) make to ambient levels. Given the complexity that accompanies estimating the contribution of sources to ambient levels of pollution, a level of uncertainty will always be present, but experience has shown that the uncertainty can be reduced sufficiently to allow development of a cost effective air quality management program.

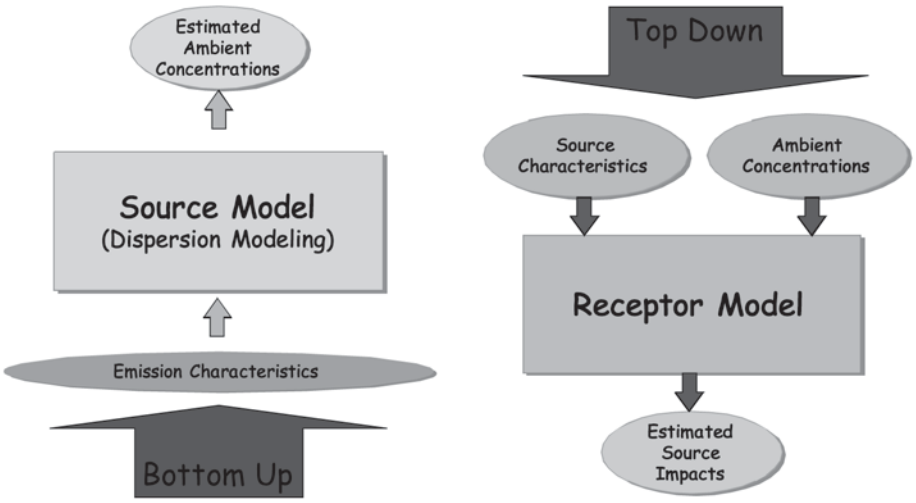
There are two basic techniques used to evaluate pollution sources. They are bottom-up evaluations that begin with activity data such as energy consumption, and estimate the emissions and concentrations accordingly; and top-down evaluations that begin with ambient air quality data and estimate the share of sources contributing to the measurement point (Figure 2.7). These techniques are not mutually exclusive. While this report is primarily about top-down source apportionment, these top-down techniques are intended to be used in conjunction with bottom-up techniques to develop a well functioning air quality management program.

"Bottom-up or Source-based Modeling Methods"

Bottom-up modeling approaches utilize sector-specific information and technical emission factors, to construct PM emission inventories. An accurate emission inventory is a critical part of an air quality management system that is capable of providing policymakers with reliable information on air pollution sources. Unfortunately, developing an accurate emission inventory is a daunting challenge. Potential gaps include inaccurate knowledge of meteorological conditions, unexpected sources, failure to adequately account for long-range transport of pollutants, and area sources such as trash burning. Also, in order to avoid cleanup expenses, polluters have incentives to hide the seriousness of their pollution emissions. Top-down techniques offer cost effective techniques to improve bottom-up analyses.

To calculate emissions, the activity data and emission factors (emissions per unit activity) are typically multiplied. Part of the appeal of the emission factor method is its simplicity.[21] Reported emission inventories for various urban areas around the world are presented in Figure 2.5

Figure 2.7 Schematics of Bottom-up and Top-down Source Apportionment



Source: Authors' calculations.

and Table A9.1. A major challenge is the accuracy of the emission factors, which often use national averages or industrial-country emission factors and control technologies.

Emission inventories are used as inputs to air quality models, which can help evaluate control strategies. Because of the complexities involved in developing emission inventories and the implications of errors in the inventory on model performance and assessments, it is important to evaluate the accuracy and degree of representation of any inventory. Annex 6 presents an array of emission inventories for multiple pollutants developed by various sectors.

When developing an emission inventory (see the examples in Figure 2.5), there is no simple formula. Every situation is different, and these differences need to be taken into consideration. This adds to the uncertainties and difficulties in comparison of sources between different cities. Also, the zonal jurisdictions add to these uncertainties. For example, for a city like Ulaanbaatar, total PM emission estimates include power plants operated by the city while cities like Santiago, Mexico City, or Pune do not include power plant emissions which might be located outside of the pollution control board's jurisdiction. Hence, this helps explain the large difference between the emissions of 213 ktons/yr for Ulaanbaatar and 150 ktons/yr for Shanghai compared to 8-66 ktons/yr of primary PM_{10} emissions for the rest of the cities on the list. That is, emission shares might be reduced on paper, but long range transport from these large point sources adds to ambient air pollution. Nonetheless, available emission inventories are continually improving, and development of standards for these inventories should accelerate the process.

Atmospheric models of dispersion, transport, and chemistry utilize information from emissions inventories to predict concentrations of air pollutants in the atmosphere. In doing so, it is necessary to resolve emission inventories in space and time, and allocate emissions to specific locations (i.e., grid square, smoke stack). Using such models, the contributions of different sources to PM pollution can be estimated. A wide range of dispersion models[22] has been published in scientific papers and even a larger number of unpublished models and special model versions exist depending on end-use such as regulatory purposes, policy support, public information and scientific research. During the process of developing an emission inventory and conducting dispersion modeling to calculate ambient particulate pollution levels, one needs to account for the precursors of secondary pollutants such as SO_2 to sulfates, NO_x to nitrates, and VOCs to secondary organic aerosols, which is important for developing countries. Also, model results should be evaluated through comparison with measured ambient levels to test the application of the model and the emission inventory developed.

During dispersion calculations, physical and meteorological conditions play an important role. Topographical features as well as certain seasonal features can either exacerbate or lessen the problems related to the severity of air pollution. For example, urban areas located in regions with temperate and cold climates, such as Xi'an, China,

[21] 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, a 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}).

[22] The air quality modeling procedures can be categorized into four generic classes: Gaussian, numerical, statistical or empirical, and physical. Gaussian models are the most widely used techniques for estimating the impact of non-reactive pollutants. Numerical models may be more appropriate than Gaussian models for urban area applications that involve reactive pollutants (this includes Lagrangian and Eulerian type numerical models), both require much more extensive input data bases and resources. Statistical or empirical techniques are frequently employed in situations where there is incomplete scientific understanding of the physical and chemical processes. Fourth, the physical modeling involves the use of wind tunnel or other fluid modeling facilities. A wide variety of dispersion models are available at different levels of simplicity and complexities.

tend to experience seasonality in their pollution patterns because of the increased fuel consumption for heating during the winter months. Thermal inversions, which are very low in the winter, reduce the dilution and dispersion capability of the atmosphere and trap air pollutants (including PM) close to the emission source. Similar effects are seen in areas that are surrounded by mountains, where mountains act as a barrier and trap air pollution close to the urban areas. Thus, given the level of complexity, it is important that reliable information on an urban area's air pollution sources and its actual air quality are gathered and analyzed when utilizing this method.

Some of the advantages of the bottom-up approach include: (i) locating pollution sources through the development of emission inventories; (ii) identifying potential sources of primary emissions; (iii) describing the relevant physical characteristics that affect the ambient levels, *viz.*, meteorological features, terrain features, e.g., a valley will affect the ambient levels differently than an urban area located near a coast; (iv) understanding the chemical processes that influence local pollutant levels, including the formation of secondary aerosols; (v) documenting the potential for secondary aerosol formation; (vi) identifying sources that would be most effective in controlling and affecting the ambient compliance levels the most; (vii) allowing for a direct estimate of the effect of changes in emissions on ambient pollutant concentrations, through emission control simulations; and (viii) providing spatial coverage of how sources impact air quality and exposure. GAINS[23] and IES[24] are examples of bottom-up studies. Currently, this approach is the best approach scientifically to assess how future emissions and meteorological changes will impact air quality, thus making it fundamental to air quality management.

"Top-down or Receptor-based Modeling Methods"

Top-down assessments begin with ambient monitoring data and then utilize models to relate measurements to specific sources of pollutants through chemical analysis of the samples.[25]

Source apportionment methods are based on the fact that different emission sources have characteristic chemical patterns or profiles of air pollution. 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.

Since this method is based on ambient data, the choice of measurement locations and number of measurements is important. The measurement locations need to represent an urban area's zones (e.g., residential, industrial, roads, agriculture, etc.) A successful study therefore requires careful planning, appropriate air sampling and analytical equipment, and

[23] Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS), developed and maintained by International Institute of Applied Systems Analysis (IIASA)—http://www.iiasa.ac.at/rains/gains

[24] Integrated Environmental Strategies (IES) of the US EPA—http://www.epa.gov/ies/

[25] Monitoring data can be taken at ground level, or at higher levels such as samples taken from aircraft or satellite imagery.

an appropriate level of technical competence to complete the necessary steps and draw appropriate conclusions.

A more detailed assessment of these methods is in the following chapters.

Advantages of this approach are that it: (i) determines if selected monitoring sites or hot spots exceed compliance levels; (ii) identifies critical pollutants of concern; (iii) may differentiate chemical composition of the PM (e.g., the primary and secondary contributions); (iv) describes source impact estimates; (v) identifies sources which would be most effective to control; and (vi) avoids the uncertainties associated with the emission inventories and meteorological inputs required for the bottom-up approach.

Top-down models face the problem of having to make actual air quality measurements of sufficient quality and resolution. Problems such as the lack of institutional or financial support to procure and maintain the relevant equipment and/or capacity to conduct appropriate chemical analysis may pose a problem. Nevertheless, many such studies have been completed in developing countries, as demonstrated in the bibliography available in Annex 7. This bibliography is more extensive than normal to allow potential adopters of top-down methods to identify individuals in their country or region that may serve as local resources as adoption decisions are made and subsequently as implementation is undertaken.

Some studies have used aircraft measurements and satellite data to gain an understanding of large scale atmospheric chemistry (for example, INDOEX[26] in 1998, ACE-Asia[27] of 2001, various NASA GTE[28] experiments in Asia, MIRAGE[29], ABC[30] of 2005 and MILAGRO-MEX[31] in 2006). However, these studies typically do not focus on identifying sources, but rather contribute to a general understanding of regional air quality. Therefore, the spatial scale is often too large to pinpoint the location of pollution sources. Satellite imagery can provide an overview of the spatial distribution of PM, but the ability to quantify PM concentrations based on these images is still under development.[32] Even when the link between satellite images and PM is better developed, models and ground measurements will still be required to infer the contributions of individual scores.

Ultimate Goal: Convergence of Bottom-up and Top-down

Ideally, both bottom-up and top-down approaches should produce the same result. However, in practice there are often large disparities between modeling and monitoring results. Experience with these analyses in industrial and developing country cities will provide a knowledge base for pursuing cost effective strategies for determining PM composition and source profiles.

Bottom-up methods pose significant technical challenges for developing countries, requiring technical expertise, time, and money to develop an accurate bottom-up emission inventory and

[26] Indian Ocean Experiment—http://www-indoex.ucsd.edu/

[27] Asia Pacific Regional Aerosol Characterization Experiment—http://saga.pmel.noaa.gov/Field/aceasia/

[28] Global Tropospheric Experiments—http://www-gte.larc.nasa.gov/

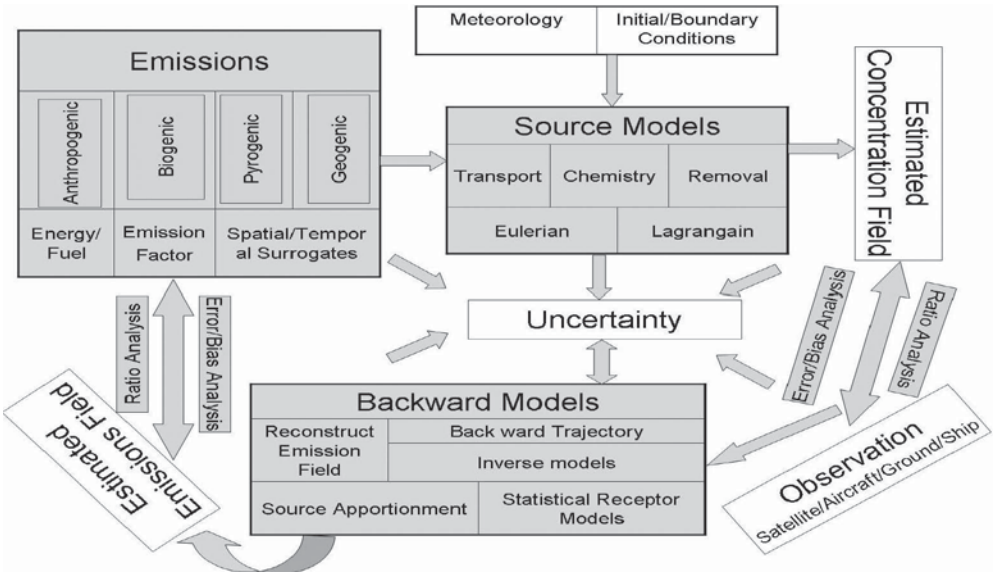
[29] Megacities Impact on Regional and Global Environments—http://mirage-mex.acd.ucar.edu/index.shtml

[30] Project Atmospheric Brown Clouds—http://www-abc-asia.ucsd.edu/

[31] Megacity Initiative: Local and Global Research Observations—http://www.eol.ucar.edu/projects/milagro/

[32] Dr. Mian Chin. "*Using Models and Satellite Data for Air Quality Studies: Challenges and Needs.*" http://www.acd.ucar.edu/Events/Meetings/Air_Quality_Remote_Sensing/Presentations/3.7.Chin.pdf

Figure 2.8 Levels of Uncertainty in Source Apportionment by Bottom-up and Top-down Methodologies



Source: Dr. Jung-Hun Woo, CGRER, The University of Iowa, USA.

an atmospheric model that is in agreement with ambient measurements. In contrast, top-down methods allow for useful information to be gained from relatively few ambient measurements. While top-down methods cannot address all relevant questions about air pollution, they can be used to identify the relative contributions of different source categories to the PM problem, and this information can be utilized to improve the bottom-up analysis and thereby a region's air quality management system. This interaction of top-down and bottom-up methods forms an iterative process of learning through which the sources of air pollution can be more precisely quantified with each new iteration. Because this iterative learning process can begin at a relatively low cost it is particularly useful for developing countries.

3 Top-down Source Apportionment Techniques[33]

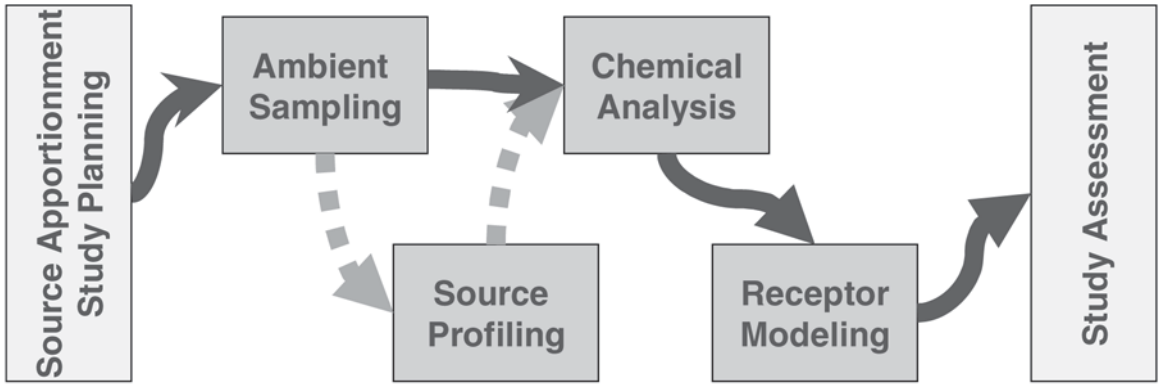
Receptor modeling of particulate pollution is the process of developing empirical relationships between ambient data at a receptor and PM emissions by source category. Top-down receptor models complement bottom-up source models that estimate concentrations from emission inventories and transport meteorology. The fundamental principle of receptor modeling is based on the assumption that mass is conserved. Based on this principle a mass balance analysis among the elements, ions, and carbons of the measured samples and source profiles is used to identify and apportion sources of PM.

This chapter deals with the techniques of sampling for aerosols, chemicals, and dusts, focusing on sampling strategy, sampling techniques, analytical methods, and interpretation of results. Overall this chapter covers most common substances that air quality investigators are likely to encounter in the field.

Methodology and Techniques

Figure 3.1 presents an outline of steps necessary to perform a source apportionment study for an urban area. This type of analysis requires real-world measurements and knowledge of potential sources. Compared to bottom-up analysis, which requires knowledge of sources and source strengths as well as detailed information on meteorology and local conditions the source apportionment methodology does not require meteorological data or complex modeling.[34] Receptor models are useful for

Figure 3.1 Steps to Perform a Top-down Source Apportionment Study



Source: Authors' calculations.

[33] This and subsequent chapters occasionally list particular manufacturers of equipment. These manufacturers are listed for illustrative purposes only and should not be construed as endorsement by the World Bank.

[34] It should be pointed out that it is possible to conduct "back-of-the-envelope" bottom-up assessments with limited information, and as off-the-shelf emission inventories and meteorological data improve the quality of these models provide coarse, first level but useful emissions information.

resolving the composition of ambient PM into components related to emission sources.

Watson et al. (2002) suggest the following approach to a receptor modeling study:

1. **Formulate conceptual model.** The conceptual model provides a plausible, though not necessarily accurate, explanation of the sources, their zones of influence, transport from distant areas, timing of emissions throughout the day, and meteorology that affects relative emissions rates, transport, dispersion, transformation, and receptor concentration. The conceptual model guides the location of monitoring sites, sampling periods, sampling frequencies, sample durations, the selection of samples for laboratory analysis, and the species that are quantified in those samples. A conceptual model can be postulated from studies in similar areas, from smaller pilot studies (e.g., analysis of archived filters), and analysis of existing air quality and meteorological data.
2. **Compile emissions inventory.** Receptor models need to be supplied with sources that are believed to be potential contributors. A receptor model inventory requires only source categories, not the locations and rates of specific sources. While ducted point source emissions can be reasonably estimated through source tests and operating records, area and mobile source emissions are inexact. The most common cause of differences between relative source contributions from source (i.e., bottom-up) and receptor models is inaccurate emission estimates. Receptor model results focus resources on those source emissions that are the most important contributors to excessive PM concentrations.
3. **Characterize source emissions.** Chemical or physical properties that are believed to distinguish among different source types are measured on representative emitters. Source profiles are the mass abundances (fraction of total mass) of a chemical species in source emissions. Source profiles are intended to represent a category of source rather than individual emitters. The number and meaning of these categories is limited by the degree of similarity between the profiles (Watson and Chow 2001).
4. **Analyze ambient samples for mass, elements, ions, carbon, and other components from sources.** As noted earlier, elements, ions (chloride, nitrate, sulfate, ammonium, water-soluble sodium, and water-soluble potassium), and organic and elemental carbon are sufficient to account for most of the particle mass. A material balance based on these measurements is a good starting point, as it shows the extent to which more specific source markers might need to be measured. Additional properties such as molecular organic compounds, isotopic abundances, and single particle characteristics further distinguish source contributions from each other, even though they may not constitute large mass fractions.
5. **Confirm source types with multivariate model.** If a sufficient number of chemically characterized ambient samples is available (more than 50), Principal Components Analysis (PCA), Positive Matrix Factorization (PMF), and UNMIX, are helpful to determine the source types and profile characteristics that might be contributors.
6. **Quantify source contributions.** The Chemical Mass Balance (CMB) model estimates source contributions based on the degree to which source profiles can be combined to reproduce ambient concentrations. The CMB attributes primary particles to their source types and determines the chemical form of secondary aerosol when the appropriate chemical components have been measured. Modern CMB software requires specification of input data uncertainty and calculates standard errors for source contribution estimates.
7. **Estimate profile changes and limiting precursors.** Source characteristics may change during transport to the receptor, the most common change being changes of sulfur dioxide and oxide of nitrogen gaseous emissions to sulfate and nitrate particles. These changes can be simulated with aerosol evolution models (Watson and Chow 2002). Secondary ammonium sulfate and ammonium nitrate involve ammonia from non-combustion

sources that may be a limiting precursor. Chemical equilibrium receptor models determine the extent to which one precursor needs to be diminished to achieve reductions in ammonium nitrate levels.

8. **Reconcile source contributions with other data analyses and source models.** Since no model, source or receptor, is a perfect representation of reality the results must be independently challenged. Receptor model source contributions should be consistent between locations and sampling times. Discrepancies between source contributions estimated by receptor models and emissions inventories or source model should be reconciled. A "weight of evidence" from multiple source attribution approaches should add confidence to the control strategies that are developed.

Receptor-based analyses provide: (i) information on the types of sources responsible for the observed pollutants; (ii) estimates of the percentage contribution of the sources for different locations during a given time period; and (iii) a basis for evaluating realistic and cost-effective strategies to reduce PM pollution. Study limitations include: (i) the need to have and apply appropriate source profiles; (ii) in some cases not being able to differentiate sources that have similar chemical composition (known as collinear), for example, cooking and open burning, or resuspended road dust and soil dust; and (iii) not being able to account for possible nonlinearities due to chemistry and the formation of secondary aerosols. While the total tons per year of emissions need to be known to support air quality modeling, providing knowledge of relative contributions is useful in informing decisions.

Several of the source apportionment methods presented here are based on analysis of the chemical composition of PM. In contrast, most routine ambient measurements, which are intended to quantify the extent of pollution and test for compliance with air pollution standards, focus on measurements of the PM mass concentration. Chemical source apportionment methods allow for relatively few measurements to be used, but require samples to be analyzed for chemical composition. Analyzing samples for chemical composition in this way provides potentially valuable information in helping to identify the sources of pollution.

Ambient Sampling

Monitoring for compliance also allows one to examine the extent and causes of elevated concentrations; study the trends in pollutant levels; locate hotspots; enhance understanding of chemical and physical properties of atmospheric pollution, which requires additional studies; apportion chemical constituents of PM to pollution sources; and evaluate adverse health effects of pollutants.

The first steps in a successful PM sampling program are selection of sampling sites, selection of a suitable sampler and size range, and selection of filter media amenable to the desired chemical analyses. Sampling procedures should be designed so that samples of the actual aerosol concentrations are collected accurately and consistently and represent the concentrations at the place and time of sampling. A sufficient number of samples from residential, roads, industrial, rural, agricultural, and background locations allow similarities and differences in concentrations to be detected.

A background study of the topography (hilly or flat) and location (seaside or continent) of the urban area will also help in selecting the sample locations to provide adequate exposure by minimizing nearby barriers and particle deposition surfaces. While selecting sampling sites, it is necessary to locate the monitor outside the zone of influence of specific emitters. The site should also be in a position to collocate measurements—other air quality and meteorological measurements that can aid in the interpretation of high or variable PM levels. If the measurements are being conducted for trend analysis, sites with long term commitment, sufficient operating space, accessibility, security, safety, power, and environmental control are necessary.

Chow et al. (2002) describe the following spatial scales on which measurements are useful.

- Collocated or indoor scale or ducted emissions (1–10m): Collocated monitors

are intended to measure the same air. Collocated measurements are often used to define the precision of the monitoring method. Different types of monitors are operated on collocated scales to evaluate the equivalence of measurement methods and procedures. The distance between collocated samplers should be large enough to preclude the air sampled by any of the devices from being affected by any of the other devices but small enough so that all devices obtain air containing the same pollutant concentrations. Effluent pipes and smoke stacks duct emissions from industrial sources to ambient air. Pollutants are usually most concentrated in these ducts and are monitored to create emissions factors and source profiles.

- Microscale (10–100 m): Microscale monitors are most often used to assess human exposure. These monitors show differences from compliance monitors when the receptor is next to a low-level emissions source, such as a busy roadway. Ambient compliance monitoring site exposure criteria avoid microscale influences even for source-oriented monitoring sites, while source emissions monitors avoid them because they represent emissions from a variety of sources. Microscale sites are usually operated for short periods to define the zones of representation for other sites and to estimate the zones of influence for ducted and non-ducted emitters. These sites are also used to estimate emission rates and compositions for nonducted sources such as suspended road dust.
- Middle scale (100–500 m): Middle-scale sites are used for human exposure studies, to evaluate contributions from large industrial facilities, and to evaluate the zones of representation of compliance sites. They are also used for process research to examine rapid changes in pollutant composition, dilution, and deposition. For air quality research, vertical resolution of pollutant concentrations on this scale (e.g., measurements on roofs of tall buildings or hilltops) elucidates mechanisms of day-to-day carryover, long-range transport, and nighttime chemistry that cannot be understood by surface measurements.
- Neighborhood scale (500 m to 4 km): Neighborhood scale monitors are used for compliance to protect public safety and show differences that are specific to activities in the district being monitored. The neighborhood-scale dimension is often the size of emissions and modeling grids used for air quality source apportionment in large urban areas, so this zone of representation of a monitor is the only one that should be used to evaluate such models. Sources affecting neighborhood-scale sites typically consist of small individual emitters, such as clean, paved, curbed roads, uncongested traffic flow without a large fraction of heavy-duty vehicles, or neighborhood use of residential heating and cooking devices.
- Urban scale (4–100 km): Urban-scale monitors are most common for ambient compliance networks and are intended to represent the exposures of large populations. Urban-scale pollutant levels are a complex mixture of contributions from many sources that are subject to area-wide control. Urban-scale sites are often located at higher elevations or away from highly traveled roads, industries, and residential wood-burning appliances. Monitors on the roofs of two- to four-story buildings in the urban core area are often good representatives of the urban scale.
- Regional-scale background (100–1000 km): Regional scale monitors are typically located upwind of urban areas and far from source emissions. Regional monitors are not necessary to determine compliance, but they are essential for determining emissions reduction strategies. A large fraction of certain pollutants detected in a city may be due to distant emitters, and a regional (rather than local) control strategy may be needed to reduce outdoor exposure. Regional-scale concentrations are a combination of naturally occurring substances as well as pollutants generated in urban and industrial areas that may be more than 100 km distant. Regional-scale sites are best located in rural areas away from local sources, and at higher elevations.

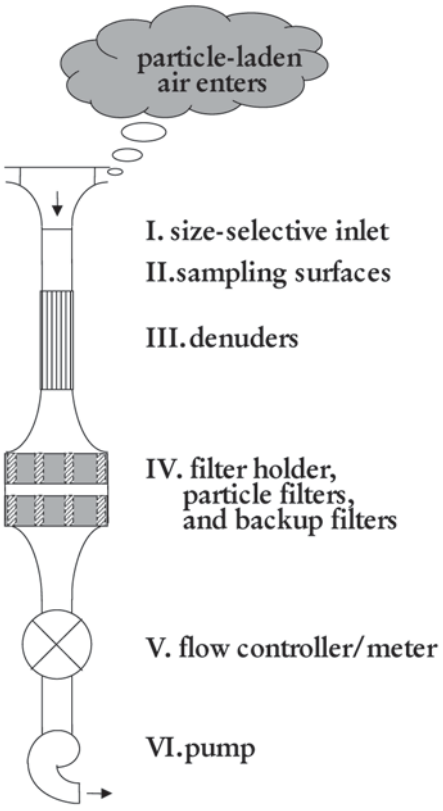
- Continental-scale background (1000–10,000 km): Continental-scale background sites are located hundreds of kilometers from emitters and measure a mixture of natural and diluted manmade source contributions. Anthropogenic components are at minimum expected concentrations. Continental-scale monitors determine the mixture of natural and anthropogenic contaminants that can affect large areas.
- Global-scale background (>10,000 km): Global-scale background monitors quantify concentrations transported between different continents as well as naturally emitted particles and precursors from oceans, volcanoes, and windblown dust.

With a limited budget, a neighborhood scale site, typically in a city center, should be the first choice. This would be followed by an urban-scale site, usually on the edge of the city in a park or schoolyard. This would be followed by a regional-scale site, outside of the populated area, often in a regional park. These allow the different zones of influence for sources to be assessed. Additional sites should be located in suspected source areas, e.g., roadsides, industrial parks. If the areas are known to be dominated by certain source contributions, these samples can be used as source profiles for receptor modeling at the other sites.

Box 3.1 presents typical components of an integrated aerosol sampling system and

Box 3.1 Components of an Aerosol Sampling System and Reference Methods for PM_{10} Measurements

- The sampling inlet should have a cut-point of 10±0.5 µm aerodynamic diameter (particle size equal and less than 10 µm in diameter is collected), as determined in a wind tunnel using liquid particles with aerodynamic diameters ranging from 3 to 25 µm and wind speeds of 2, 8, and 24 km/hr.
- The flow rate should remain stable over a 24-hour period, regardless of filter loading, within ±5% of the initial reading for the average flow and within ±10% of the initial flow rate for any instantaneous flow measurement. Sample volumes are adjusted to sea level pressure and 25°C.
- Measurement precision, determined by repeated collocated sampling, should be within ±5 µg/m^3 for concentrations less than 80 µg/m^3 or ±7% of measured PM_{10} for concentrations exceeding 80 µg/m^3 for a 24-hour period.
- Filter media should collect more than 99% of 0.3 µm particles, have an alkalinity of less than 25 micro-equivalents/gram, and should not gain or lose weight equivalent to more than 5 µg/m^3, estimated from the nominal volume sampled over a 24-hour period.
- Prior to weighing, filters should be equilibrated at a constant temperature, within ±3% between 15°C and 30°C, and at constant relative humidity within ±5% between 20% and 45%.



Source: Watson, John G. and Judith C. Chow (2001).

reference methodology for PM_{10} measurements. Having a properly formulated model reduces the cost and time for the source apportionment task as it will help to select the right locations and number of sampling sites, species to be analyzed in ambient PM, and number of samples to be taken and analyzed.

Table 3.1 presents a list of commonly used samplers. The major prerequisite in selecting a sampling system is to determine what size range of particles is to be monitored and the method of chemical analysis (following section). The chemical analysis method will dictate the type of filter to use, compatible with the sampler and the type of results expected from the study. Several air sampling filter types are available, and the specific filter used depends on the desired physical and chemical characteristics of the filter and the analytical methods used. No single filter medium is appropriate for all desired analyses. Particle sampling filters consist of a tightly woven fiber mat or plastic membrane penetrated by microscopic pores.

Annex 1 presents a list of commonly available and utilized aerosol sampling components—inlets, filter holders, sampling surfaces, and monitors. Commonly used samplers are briefly discussed below.

In developing countries, *Continuous monitors* are commonly used to characterize diurnal patterns of exposure and emissions and are very useful in collecting samples during extremely high or low particulate periods. Continuous monitoring data can be used to provide more timely data reports to the public and collection of data on a more real time basis. Currently available continuous monitors for mass monitoring include the *Tapered Element Oscillating Microbalance* (TEOM®), *Beta Attenuation Monitor* (BAM), and the *Pressure Drop Tape Sampler* (CAMMS). In general, these samplers are not used for

Table 3.1 List of Aerosol Samplers

Sampling Method	Sampler Description	Particle size (μm)	Flow Rate (l/min)
Hi-volume sampler*	Using cyclone-type inlet, critical flow device, and 20.3 cm × 25.4 cm glass filters	TSP (no inlet) ≤ 10 or ≤ 2.5	1,133
Medium-volume sampler*	Using impaction-type inlet, 47mm Teflon membrane and quartz-fiber filter. Samples are collected simultaneously onto two filter substrates.	≤ 10 or ≤ 2.5	113
Low-volume dichotomous sampler**	Using impaction-type PM_{10} inlet, 2.5μm virtual impactor assembly and 37 mm $PM_{2.5}$ and $PM_{2.5-10}$ filter holders	< 2.5, 2.5 –10	16.7
Mini-volume sampler	Using greased impaction inlets for $PM_{2.5}$ and PM_{10}	≤ 10 or ≤ 2.5	5.0
β-attenuation monitor**	Using impaction-type PM_{10} inlet and 40- mm filter tape	≤ 10 or ≤ 2.5	–16.7
TEOM® (Produced by Thermo Fisher Scientific which acquired the original manufacturer—Rupprecht & Patashnik)**	Using impaction-type PM_{10} inlet, internal tapered element oscillating microbalance, and 12.7 mm diameter filter	≤ 2.5	–3 (with bypass flow of 13.7)

Source: Chow, 1995.

* Reference Method; ** Equivalent Method

PM chemical measurements used for receptor model studies.

The *Federal Reference Method (FRM)* samplers are filter-based methods that require a fixed flow rate and generally produce data of good accuracy and precision for $PM_{2.5}$ and PM_{10}. FRMs are specified for determining compliance only and are not used for chemical speciation in their FRM modes. Unlike the continuous monitors, data from a FRM monitor may not be available until four to twelve weeks after the actual measurement was made and cannot be used if the primary purpose is to monitor real time air quality. Monitoring networks for $PM_{2.5}$ are expensive and labor intensive to operate and maintain.

The *Dichotomous Sampler (Dichot)*[35] is a particulate matter sampler for the simultaneous collection of the fine and coarse particles contained in PM_{10}. The unique design of the PM_{10} inlet allows only particles smaller than 10 microns to enter the virtual impactor. This virtual impactor is used to segregate the air sample into two fractions by accelerating the air sample through a nozzle and then deflecting the air at a right angle. Most $PM_{2.5}$ (fine fraction) will follow the higher airflow path and be collected on a fine particulate filter. $PM_{10\text{-}2.5}$ (coarse fraction) has sufficient inertia to impact into the chamber below the nozzle and is collected on a coarse particulate filter. The virtual impactor also eliminates possible problems of particle bounce and re-entrainment often experienced in other particle size impactor methods.

The *High-volume samplers* used for particulate measurements have the sample system as an integral component of the sampler shelter. The function of this air sampler is to keep the air flow constant, as the particulate loading increases over time. Unlike traditional systems though, the need for mechanical sensors and controls (i.e., velocity sensors, strain gauges) has been eliminated. In more comprehensive monitoring stations where a number of parameters are being measured, it is common to use a larger-scale system incorporating a wide bore vertical sample line, a manifold to permit individual analyzers to withdraw the air simultaneously, and a large pump or fan to move air through the common sample line.

The *Thermo Fisher Scientific PM_{10} monitor* is a TEOM® a filter-based measurement system to continuously measure particulate mass at concentrations between 5 $\mu g/m^3$ and several g/m^3 on a real-time mass monitoring basis. The instrument calculates mass rate, mass concentration, and total mass accumulation on exchangeable filter cartridges that are designed to allow for future chemical and physical analysis. In addition, this instrument provides for hourly and daily averages. This system operates on the principal that particles are continuously collected on a filter cartridge mounted on the tip of a tapered hollow glass element. The PM_{10} inlet is designed to allow only particulate matter 10 µm in diameter to remain suspended in the sample air stream as long as the flow rate of the system is maintained at 16.7 l/min. The monitor can also be operated as a TSP monitor or as a $PM_{2.5}$ monitor by changing the inlet head.

The *MiniVol™ Portable Air Sampler (MiniVol™)*[36] can be configured to collect $PM_{2.5}$, PM_{10}, or TSP samples, however only one type can be selected at a time. The MiniVol's pump draws air at 5 l/min through a particle size separator (impactor) and then through a 47mm filter. The PM_{10} and $PM_{2.5}$ separation is achieved by impaction, or a TSP sample can be collected by removing the impactor(s). Figure 3.2 presents an assembly of the sampler, which is widely used for source apportionment studies around the world (see Chapter 4 for applications).

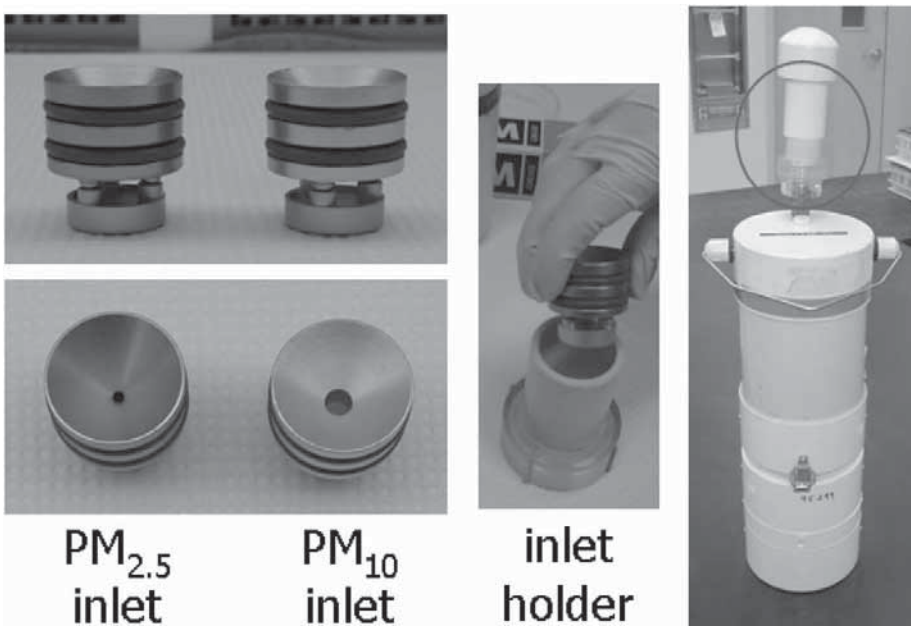
In many developing countries, locally made samplers are often used. It is necessary for quality control to standardize the samplers with other standard/proven samplers. For example, MiniVol™ samplers are relatively inexpensive (~ U$3,500), can be used for PM_{10} and $PM_{2.5}$, and are easy to operate and maintain.

Annex 2 presents the characteristics of filter media available along with their suppliers. Filter cost is generally a small fraction of the

[35] Dichot Sampler—http://www.pacwill.ca/dichot.htm

[36] Minivol Sampler—http://airmetrics.com/products/minivol/index.html

Figure 3.2 MiniVol™ Sampler and PM Filter Assembly



Source: Watson and Chow (2003).

cost of monitoring. Ringed Teflon-membrane filters are typically the most costly (US$4.50 for each 47 mm diameter filter), with cellulose-fiber and glass-fiber filters (¢0.25 for each 47 mm diameter filter) being the least expensive. The validity of the measurement should not be compromised because one filter is less expensive than another. Filters should be consistently manufactured and available at reasonable costs and suitable to the equipment available to conduct chemical analysis of the samples. Filters should be procured well in advance of a monitoring program and in sufficient quantity to last the duration of the study. Refer to Annex 1 for pictures of filter media and holders.

Source Profiling[37]

A key component needed to conduct a top-down analysis is a collection of source profiles reflective of the emission sources impacting the urban area being studied. A source profile identifies the quantities of specific air pollutants (elements and ions) emitted from individual sources. It provides important data used for source apportionment as these determine the next level of assessment and provide the basis for estimating the contribution of various sources to ambient concentrations.

Many of the source profiles currently available are from industrial countries, where the mix of fuels used and combustion technologies employed are often different from those utilized in developing countries. The bibliography (Annex 7) identifies profile references from many developing countries. Additional studies are underway to determine source profiles for developing countries, but this avenue of research is still in its infancy.[38] Annex 3 describes a series of source sampling techniques as outlined in Chow, 1995. Figure 3.3 presents examples of how samples for source profiles were collected from

[37] Note that this step is conducted in parallel to ambient sampling. The sampling methods here are similar to ambient sampling with more proximity to the sources and the profiling itself includes the next step "Chemical Analysis."

[38] Although the sampling process for developing source profiles is similar to ambient sampling, lack of technical and financial resources has led to more ambient sampling than source profiling in developing countries, where monitoring is conducted more for regulatory purposes. In recent years, this has been changing and more efforts are being devoted to source profiling.

Figure 3.3 Sampling for Source Profiles (a) Road Side Sampling (b) Stack Testing (c) Real World Cooking and (d) Simulated Cooking

Source: Watson and Chow (2005).

road side emissions, stack testing, and cooking. Because a source profile is the key to linking air samples with sources, the more accurate a source profile is, the more likely that quality results will follow. The dotted arrows in Figure 3.1 indicates that customized source profiles (the ideal situation) can be developed for urban area being studied, or source profiles from other studies can be utilized.

Source profiles may consist of a wide range of chemical components, including elements, ions, carbon fractions, organic compounds, isotopic abundances, particle size distributions and shapes. In top-down analysis whatever is measured at the source must also be measured at the receptor, and vice versa. Source markers are sought that are abundant in one source type, but are minimally present in other source types. These markers must also have relatively stable ratios with respect to other components in the source profile. Table 3.2 presents elemental ionic and carbonaceous characteristics of various PM sources. When a source has a chemical marker, it is easy to identify the dominant source, and receptor modeling (in the coming sections) helps estimate the contribution of these sources based on factor analysis (Table 3.3). For example, biomass burning has a strong signal in potassium (K), while dust contains aluminum (Al) and silicon (Si).

Three classes of carbon are commonly measured in aerosol samples collected on quartz-fiber filters: 1) organic, volatilized or non-light absorbing carbon; 2) elemental or light absorbing carbon, generally referring to particles that appear black and are also called "soot" "graphitic carbon" or "black carbon;" and 3) carbonate carbon. Carbonate carbon

Table 3.2 Elements Measured in Chemical Analysis and Possible Sources

Elements	Possible Sources
Al, Si, Ca, Ti, Mn	Soils, Dust
S	Fossil fuels, Anthropogenic, and Biomass burning, Oceans, Soil Erosion
Cl	CFC's, Soil, Sea salt and Anthropogenic sources
K	Coal combustion, Biomass burning, Biomass fuels
V	Fuel oil and Steel factories
Cr	Emissions from Chemical plants, Cement dust and Crustal sources
Fe	Soils, Smelting industry
Ni	Heavy fuel oil combustion
Cu	Industries and Waste treatment
Zn	Combustion of coal and heavy fuel oil
As	Solid mineral fuels, Heavy fuel oil, Volcanoes, Smelting industry
Se	Heavy fuel oil and Glass production
Br	Gasoline, Transportation industry
Rb	Crustal sources
Pb	Paint industry, Leaded fuel use (banned)

Source: Authors' calculations.

(e.g., K_2CO_3, Na_2CO_3, $MgCO_3$, $CaCO_3$,) can be determined on a separate filter section by measurement of the carbon dioxide evolved upon acidification. Carbon is typically separated by volatility; organic carbon is released at fairly low temperatures and elemental carbon at much higher temperatures. These broad classes of carbon are often combined with elemental analysis.

Organic marker compounds have become more useful as many toxic elements formally used as markers are removed from emission sources (e.g., lead from gasoline engine exhaust). Analysis using organic marker compounds can be quite useful when identifying contributions of sources that emit primarily carbonaceous particles. Further detail in organic characterization may be incorporated into source profiles (Chow et al. 2007a, 2007b). Some individual organic molecules such as hopanes are prevalent in particular combustion sources. Analysis using these compounds can be quite useful when identifying contributions of sources that emit primarily carbonaceous particles. For example, this analysis may distinguish between diesel and gasoline exhaust (see Figure A3.4) and between soil dust and road dust. Organic compounds are also useful in distinguishing emissions from ethanol fueled versus gasoline fueled vehicles.

Studying the organic component of sources is also important because this complex mixture of organic compounds, many of which can cause cancer and genetic mutations, makes up approximately 30 to 50 percent of the $PM_{2.5}$ in urban environments. By utilizing modern extraction methods organic compounds can be measured at costs comparable to those for elements, ions, and carbon.

Example profiles (Zielinska et al., 1998) are presented in Annex 3. Song et al., 2006, presents a series of source profiles for $PM_{2.5}$ samples collected in Beijing, China for biomass burning, secondary sulfates, secondary nitrates, coal combustion, industry, motor vehicles, yellow dust, and road dust. Refer to Annex 3 for more examples and references.

Methods of Analysis for Ambient and Source Samples

Physical and chemical analysis of the measured particulate matter features include shape and color, particle size distribution (number), and chemical compounds. Temporal and spatial variation of these properties at receptors also helps to assign pollution levels to source types. Although most of these features can be used to identify source types, the only measures that can be used to determine quantitatively a source contribution to air particulate levels are component concentrations described in the source profiles. Common methods utilized by various groups are outlined in Table 3.4.

Table 3.3 Typical Elemental, Ionic, and Carbon Source Markers

Source Type	Dominant Particle Size	Particle Abundance in Percent Mass			
		< 0. 1%	0.1 to 1%	1 to 10%	> 10%
Paved Road	Coarse (2.5 to 10 μm)	Cr, Sr, Pb, Zr	SO_4^{2-}, Na^+, K^+, P, S, Cl, Mn, Zn, Ba, Ti	EC, Al, K, Ca, Fe	OC, Si
Unpaved Road Dust	Coarse	NO_3^- , NH_4^+, P, Zn, Sr, Ba	SO_4^{2-}, Na^+, K^+, P, S, Cl, Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si
Construction	Coarse	Cr, Mn, Zn, Sr; Ba	SO_4^{2-}, K^+, S, Ti	OC, Al, K, Ca, Fe	Si
Agriculture Soil	Coarse	NO_3^-, NH_4^+, Cr, Zn, Sr	SO_4^{2-}, Na^+, K^+, S, Cl, Mn, Ba, Ti	OC, Al, K, Ca, Fe	Si
Natural Soil	Coarse	Cr, Mn, Sr, Zn, Ba	Cl^-, Na^+, EC, P, S, Cl, Ti	OC, Al, Mg, K, Ca, Fe	Si
Lake Bed	Coarse	Mn, Sr, Ba	K^+, Ti	SO_4^{2-}, Na^+, OC, Al, S, Cl, K, Ca, Fe	Si
Motor Vehicle'83-205	Fine (0 to 2.5 μm)	Cr, Ni, Y, Sr, Ba	Si, Cl, Al, Si, P, Ca, Mn, Fe, Zn, Br, Pb	Cl , NO_3^- , SO_4^{2-}, NH_4^+, S	OC, EC
Vegetative Burning	Fine	Ca, Mn, Fe, Zn, Br, Rb, Pb	NO_3^-, SO_4^{2-}, NH_4^+, Na+, S	Cl–, K^+, Cl, K	OC, EC
Residual Oil Combustion	Fine	K+, OC, Cl, Ti, Cr, Co, Ga, Se	NH_4^+, Na', Zn, Fe, Si	V, OC, EC, Ni	S, SO4'
Incinerator	Fine	V, Mn, Cu, Ag, Sn	K', Al, Ti, Zn, Hg ,	NO_3^-, Na^+, EC, Si, S, Ca, Fe, Br, La, Pb	SO_4^{2-}, NH_4^+, OC Cl
Coal-Fired Boiler	Fine	Cl, Cr, Mn, Ga, As, Se, Br, Rb, Zr	NH_4^+, P K, Ti, V, Ni, Zn, Sr, Ba, Pb	SO_4^{2-}, OC, EC, Al, S, Ca, Fe	Si
Oil Fired Power Plant	Fine	V, Ni, Se, As, Br, Ba	Al, Si, P, K, Zn	NH_4^+, OC, EC, Na, Ca, Pb	S, SO_4^{2-}
Smelters	Fine	V, Mn, Sb, Cr, Ti	Cd, Zn, Mg, Na, Ca, K, Se	Fe, Cu, As, Pb	S
Marine	Fine and Coarse	Ti, V, Ni, Sr, Zr, Pd, Ag, Sn, Sb, Pb	Al, Si, K, Ca, Fe, Cu, Zn, Ba, La	NO_3^-, SO_4^{2-} , OC, EC	Cl^-, Na^+, Na, Cl

Source: Chow, 1995.

The *Gravimetric analysis* is used almost exclusively to obtain mass measurements of filters. The basic method of gravimetric analysis is fairly straightforward—the net PM mass on a filter is determined by weighing the filter before and after sampling with a gravimetric balance in a temperature and relative humidity controlled environment. The sample filters of $PM_{2.5}$ and PM_{10} have to be equilibrated at low temperatures and relative humidity conditions to remove liquid water while avoiding particle volatilization.

In *Ion Chromatography (IC),* the aerosol samples are analyzed for the anions (fluoride, phosphate, chloride, nitrate, and sulfate) and cations (potassium, ammonium, and sodium). All ion analysis methods require a fraction of the filter to be extracted in deionized distilled water and then filtered to remove insoluble residues prior to analysis. The IC is especially desirable for particulate samples because it provides results for several ions with a single analysis, has low detection limits, and uses a small portion of the filter extract. This is the most common

Table 3.4 Analytical Techniques for PM Samples

Measurement	Suitable Analytical Technique
Particle mass	Gravimetric analysis, β-gauge monitoring
Ions (F^-, Cl^-, NO_2^-, PO_4^{3-}, Br^-, SO_4^{2-}, NO_3^-, K^+, NH_4^+, and Na^+)	Ion Chromatography (IC) or Automated Colorimetric Analysis (AC)
Elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Mo, Pd, Ag, Cd, In, Sn, Sb, Ba, La, Au, Hg, Ti, Pb and U)	XRF, PIXE, INAA, ICP, Emission Spectroscopy, AAS
Total Carbon, Elemental Carbon, Organic Carbon, Carbonate Carbon, Thermal Carbon Fractions	Thermal Manganese Oxidation Method, Thermal Optical resistance (TOR) or Thermal/ Optical Transmission (TOT) Method
Individual organic compounds	Solvent Extraction Method followed by Gas Chromatography-Mass Spectrometer (GC-MS), High Performance Liquid Chromatography (HPLC)
Total Carbon	Thermal Combustion Method
Absorbance (light absorbing carbon)	Optical Absorption, Transmission Densitometry, Integrating Plate or Integrating Sphere Method

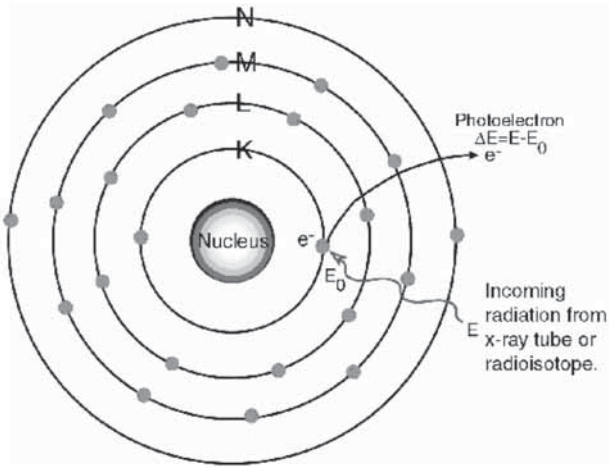
Source: Chow, 1995.

method utilized for ion analysis, an important stage for sample analysis.

The *Atomic Absorption Spectrophotometry (AAS)* is useful for a few elements, but it requires a large dilution of the sample. Several simple ions, such as sodium, magnesium, potassium, and calcium, are best quantified by AAS.

In *XRF analysis*, the sample is irradiated with a beam of X-rays in order to determine the elements present in the sample. The principle behind this technique is that some of the X-rays will be scattered, but a portion will be absorbed by the elements contained in the sample. Because of their higher energy level, they will cause ejection of the inner-shell electrons. The electron vacancies will be filled in by electrons cascading from outer electron shells. However, since electrons in outer shells have higher energy states than the inner-shell electrons, the outer shell electrons must give off energy as they cascade down. The energy given off is in the form of X-rays, the phenomenon is referred to as X-ray fluorescence (as seen in Figure 3.4) Many elements can be measured simultaneously with the quantity of each element determined from the intensity of the X-rays. This analytical technique is non-destructive, has a detection limit higher than other analytical techniques, requires minimal sample preparation and is relatively inexpensive. XRF uses thin-film deposits on Mylar films for calibration.

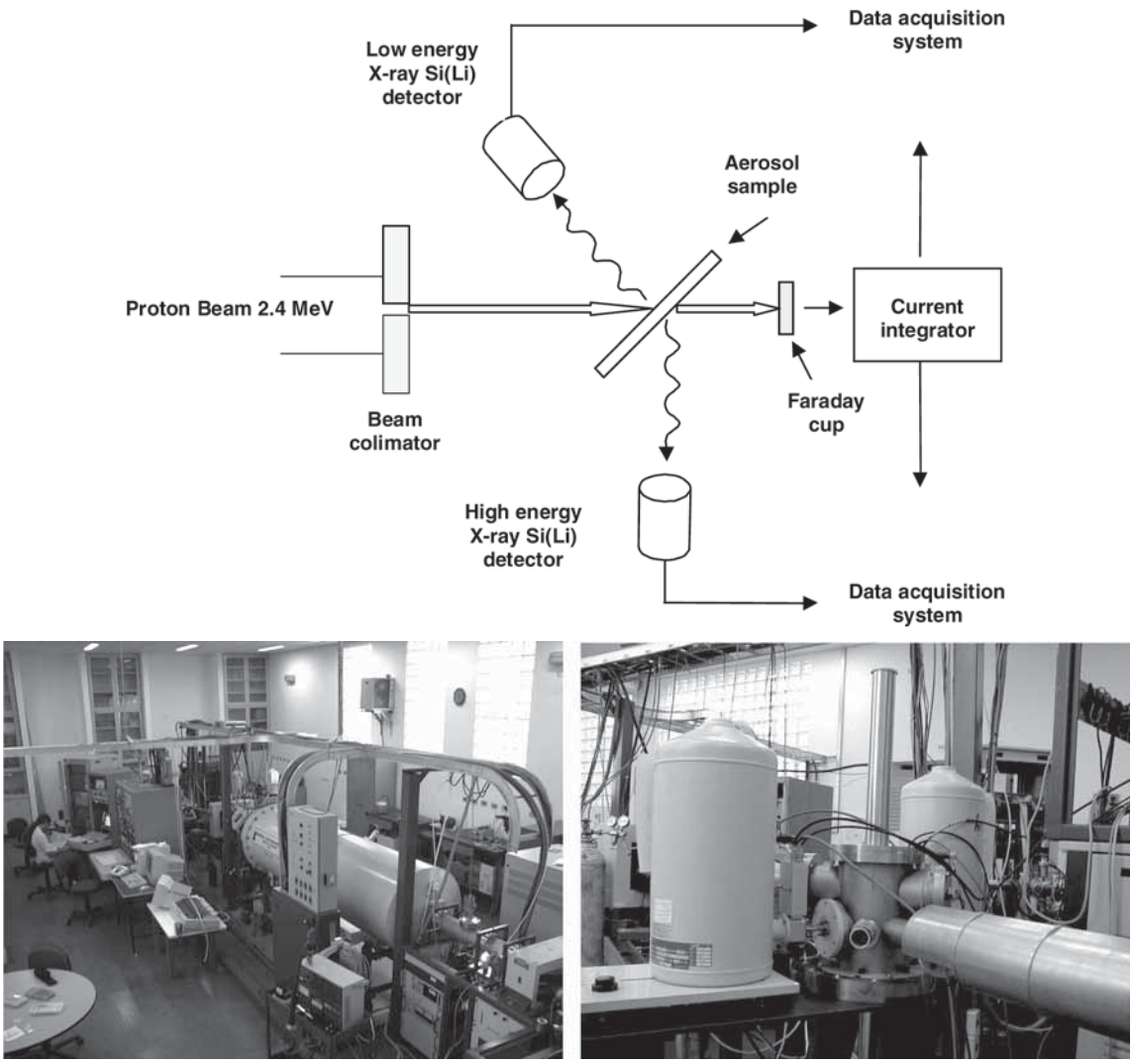
Figure 3.4 Schematic Diagram of XRF



Source: Authors' calculations.

In *PIXE analysis*, similar to XRF, the sample is irradiated by high-energy protons, to remove inner shell electrons. Schematics of its operations are presented below along with pictures from The University of Sao Paulo, Brazil (Figure 3.5).

Figure 3.5 Schematic Diagram and Pictures of PIXE



Source: Dr. Paulo Artaxo. University of Sao Paulo, Brazil.

Characteristic X-rays are detected using the same detection methods as in XRF. This multi-elemental analytical technique can measure more than 25 elements, including total carbon in the sample, in a short time frame due to higher cross-sections compared to XRF. Two developing country institutions which utilize PIXE extensively for source apportionment analysis are the University of Sao Paulo, Brazil, and Bangladesh Atomic Energy Center, Dhaka, Bangladesh (see case studies in Chapter 4).

The *Inductively Coupled Plasma (ICP)* and *Instrumental Neutron Activation Analysis (INAA)* are not commonly applied to aerosol analysis because ICP requires destroying the filter, while INAA saturates the filter and makes it radioactive. In INAA, when the sample is exposed to a large neutron thermal flux in a nuclear reactor or accelerator, the sample elements are transformed into radioactive isotopes that emit gamma rays that can be measured to determine the specific isotopes present. INAA is a highly sensitive, non-destructive, multi-element method that can be used to measure more than 40 elements, and does not generally require significant sample preparation. It cannot however quantify elements such as sulfur, and lead. ICP is complementary to XRF and PIXE, offering lower

detection limits for some of the rare earth species (see Annex 4).

Several *Thermal-Optical methods (TOT and TOR)* are currently in use for the analysis of carbonaceous aerosols (Watson et al. 2005). Thermal-optical analyzers operate by liberating carbon compounds under different temperature and oxidation environments. A small portion is taken from a quartz-fiber filter sample and placed in the sample oven purged with inert gas such as helium. In general, thermal-optical methods classify carbon as "organic" or "elemental." Organic carbon is non-light absorbing carbon that is volatilized in helium as the temperature is stepped to a preset maximum (850°C). Elemental carbon is light-absorbing carbon and any non-light absorbing carbon evolved after pyrolysis. Depending on the sampling environment, carbonates are also analyzed in the sample. The IMPROVE, a thermal optical reflectance (TOR) method (Chow et al., 2007), which is now in use at all U.S. speciation monitoring sites, yields eight thermally-derived carbon fractions that have been found useful for source apportionment.

"Elemental" and "black" carbon refer to similar fractions of the carbonaceous aerosol: strongly light-absorbing, thermally-stable carbon that is commonly called "soot." The term "elemental" usually refers to the results determined with thermal-optical methods, while the term "black" usually refers to a measurement by optical methods such as reflectance or transmittance. Because there are no analytical standards for elemental and black carbon, all values are defined by the measurement method itself, and two techniques applied to the same sample may yield different results. Therefore, it is important that both source profiles and ambient measurements use the same carbon measurement method.

The *Ion Beam Analysis (IBA)* is a suite of accelerator-based techniques including PIXE. Other techniques are: the particle induced γ-ray emission (PIGE) which is used to measure light elements such as boron, fluorine, sodium, magnesium and aluminum and the proton elastic scattering analysis (PESA). PESA is used to measure hydrogen in order to distinguish between elemental and organic carbon in samples. Rutherford backscattering analysis (RBS) is for the measurement of carbon, nitrogen and oxygen mainly for charge calibration purposes. IBA measures more than 30 elements. With the addition of PIGE and PESA, IBA allows for the detection of light elements, useful for finger printing, source apportionment and estimation of organic carbon.

The *Gas Chromatography-Mass Spectrometer (GC-MS)* is a complex system which is used for quantitative and qualitative analysis of organic compounds. This instrument separates chemical mixtures (the GC component) and identifies the components at a molecular level (the MS component). It is one of the most accurate tools for analyzing environmental samples. The GC works on the principle that a mixture will separate into individual substances when heated. The heated gases are carried through a column with an inert gas (such as helium). As the separated substances emerge from the column opening, they flow into the mass spectrometer. Mass spectrometry identifies compounds by the mass of the analyzed molecule. A "library" of known mass spectra, covering several thousand compounds, is stored on a computer. Samples of organic carbon source profiles from various sources are presented in Figures A3.3 and A3.4. Thermal desorption GC/MS methods developed in China can obtain profiles and ambient data on a small filter punch similar to that used for carbon analyses.

The detection limits from several different elemental analysis methods are compared in Annex 4. The analytical measurements should be selected based on the resources available for the study, species to be measured and the types of ambient samples collected. It is again noted that the sampling and analysis should be planned together as certain analytical measurements cannot be performed unless the samples have been collected in a specific way using a specific filter (see Annex 2).

Individual organic compounds present in PM are potentially useful for source apportionment

by receptor modeling (see the case study of India in Chapter 5). Given the multitude of organic compounds present in the atmosphere, measurement of many members of appropriate compound classes provides very high resolution of sources.

The organic chemical species of interest for receptor modeling will be mainly present in the fine fraction. The study of organic compounds is needed particularly for the identification and assay of particles from sources that release mostly carbonaceous particles that provide little or no signal via the elements observed (i.e., the lack of an elemental marker) (see Figure A3.3 and Figure A3.4). Polycyclic aromatic hydrocarbons (PAHs) have been the most extensively studied. Analytical methods for PAHs include gas chromatography/mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC). It should be noted that analysis for individual organic compounds, for example PAH, is resource consuming and their levels in ambient air are normally too low to be detected if the amounts of particulate material are not large enough.

Table 3.5 presents upfront costs of most of the commonly available equipment for chemical analysis. In general, XRF is a preferred method for elemental-analysis measurement of airborne particles because: it obtains many elemental (Na-U) concentrations with minimal labor; it requires minimal sample preparation; it is characterized by low detection limits, short analysis time, high sensitivity for many elements, without sample destruction; and above all it has good accuracy, precision, and reproducibility, with the possibility of automation. Additionally, the analyzed filters can be used for additional analysis by other methods. Although PIXE also uses a similar principle, the number of analyzed elements is less than the number of elements analyzed by XRF. The minimum detection limit of PIXE is also higher than XRF. However, caution is noted that deposits on fiber filters in XRF causes x-ray absorption biases for light elements because the particles penetrate deep into the filter, and the intervening filter material attenuates the emitted X-rays. Membrane filters such as Teflon and Polycarbonate are commonly used to obtain a surface deposit for these analyses.

Table 3.5 Cost of Major Equipment for the Source Apportionment Laboratory

Analysis	Manufacturer/Model	Cost (US$)
Gravimetry	Cahn 33 Microbalance	$7,000
Gravimetry	Mettler M5 Microbalance	$15,000
IC	Dionex 500 (cation and anion)	$70,000
AAS	Varian	$70,000
XRF	Pan Analytical	$150,000
ICP/MS	Thermo Electron	$300,000
Thermal/Optical Carbon Analysis	Atmoslytic	$70,000
Automated Colorimetric Spectroscopy	Astoria Pacific	$60,000
Thermal Desorption and Pyrolysis	Agilent Technologies	$110,000
Solvent Extraction and Evaporation	Dionex 500 (cation and anion)	$53,000
Microwave Digester	Mars 5	$25,000
Equipment at Desert Research Institute, USA		

Source: Information provided by Dr. Judith Chow (2008).

Note: Table 3.5 is a listing of equipment available at one research institute. Listing of these manufacturers should not be construed as an endorsement. There are other manufacturers of these pieces of equipment.

Receptor Modeling

Receptor models apportion an ambient mixture of pollutants to the contributing pollution sources. These models use information on the chemical composition of ambient measurements at a receptor, along with the chemical profiles of different sources, to try to construct the relative contributions of those sources to the ambient measurement. Enrichment factor, chemical mass balance, multiple linear regression, eigenvector, edge detection, neural network, aerosol evolution, and aerosol equilibrium models have all been used to apportion air pollution and more than 500 citations of their theory and application document these uses.

Based on the number of samples, analytical data collected on the samples, and the information on source profiles, a mass balance equation for receptor modeling from the m chemical species in the n samples originating from p independent sources can be described as $X_{ij} = \sum_{k=1}^{p} C_{ik} S_{kj}$ where X_{ij} is the i^{th} chemical concentration measured in the j^{th} sample, C_{ik} is the gravimetric concentration of the i^{th} element in the material from the k^{th} source, and S_{kj} is the total airborne mass concentration of the material from the k^{th} source contributing to the j^{th} sample.

This is the Chemical Mass Balance (CMB) model, which has several solutions (e.g., effective variance, Positive Matrix Factorization (PMF), Principal Component Analysis (PCA), Factor Analysis (FA), Constrained Physical Receptor Model (COPREM), and UNMIX). Table 3.6 summarizes various models available for conducting receptor modeling, their requirements, advantages, and limitations.

The effective variance *CMB model*[39] is one of several receptor models that have been widely applied to source apportionment studies. CMB version 8.2, developed by Watson et al. (1997), is the newest version of the CMB model provided by the U.S. Environmental Agency, which includes the features of Windows-based and menu-driven operation. CMB requires speciated profiles of potentially contributing sources and the corresponding ambient data from analyzed samples collected at a single receptor site. CMB is ideal for localized non-attainment problems (i.e., not meeting emission standards), as well as for confirming or adjusting emission inventories. The basic idea of CMB8.2 is that composition patterns of emissions from various classes of sources are different enough that one can identify their contributions by measuring concentrations of many species in samples collected at a receptor site, hence requiring precise information regarding the chemical composition for each source category in the city or region (local specific source profiles). Output from this model includes the fraction contribution from each source and associated uncertainties.

The *Positive Matrix Factorization (PMF) method,*[40] developed by Paatero and Tapper (1994), uses the uncertainty of measured data to provide an optimal weighting across the sources. Application of PMF requires that error estimates for the data be chosen judiciously so that the estimates reflect the quality and reliability of each of the data points. This feature provides one of the most important advantages of PMF, the ability to handle missing and below-detection-limit data by adjusting the corresponding error estimates. PMF (and the UNMIX method described below) provide source factors, but these must be associated with real source categories by the receptor modeler. PMF (and UNMIX) also does not determine the number of contributing source types, and this number must also be selected by the modeler. PMF and UNMIX solutions are only plausible when the source factors are demonstrated to be similar to measured source profiles. In PMF, constraints on the results such as non-negativity of the factors are integrated into the computational process. This is the major difference from other multivariate methods. This method was applied is the case studies on Bangkok and Dhaka (discussed in the next chapter).

The *Constrained Physical Receptor Model (COPREM) model*, developed by Wahlin (2003)

[39] Latest version of the CMB8.2 model, which is MS Windows based, can be downloaded at http://www.epa.gov/scram001/receptor_cmb.htm

[40] PMF model 1.1 is available at http://www.epa.gov/heasd/products/pmf/pmf.htm

Table 3.6 Review of Receptor Models—Requirements, Strengths, and Limitations

Receptor Model	Model Requirements	Strengths	Limitations
Effective Variance CMB	Source and receptor measurements of stable aerosol properties that can distinguish source types. Source profiles (mass abundances of physical and chemical properties) that represent emissions pertinent to the study location and time. Uncertainties that reflect measurement error in ambient concentrations and profile variability in source emissions. Sampling periods and locations that represent the effect (e.g., high PM, poor visibility) and different spatial scales (e.g., source dominated, local, regional).	Simple to use, software available. Quantifies major primary source contributions with element, ion, and carbon measurements. Quantifies contributions from source sub-types with single particle and organic compound measurements. Provides quantitative uncertainties on source contribution estimates based on input data uncertainties and colinearity of source profiles. Has potential to quantify secondary sulfate contributions from single sources with gas and particle profiles when profiles can be "aged" by chemical transformation models.	Completely compatible source and receptor measurements are not commonly available. Assumes all observed mass is due to the sources selected in advance, which involves some subjectivity. Does not directly identify the presence of new or unknown sources. Typically does not apportion secondary particle constituents to sources. Must be combined with profile aging model to estimate secondary PM. Much co-linearity among source contributions without more specific markers than elements, ions, and carbon.
Injected Marker CMB Tracer Solution	Non-reactive marker(s) added to a single source or set of sources in a well-characterized quantity in relative to other emissions. Sulfur hexafluoride, perfluorocarbons, and rare earth elements have been used.	Simple, no software needed. Definitively identifies presence or absence of material from release source(s). Quantifies primary emission contributions from release source(s).	Highly sensitive to ratio of marker to PM in source profile; this ratio can have high uncertainty. Marker does not change with secondary aerosol formation—needs profile aging model to fully account for mass due to "spiked" source. Apportions only sources with injected marker. Costly and logistically challenging.
Enrichment factor (EF) CMB solution	Inorganic or organic components or elemental ratios in a reference source (e.g., fugitive dust, sea salt, primary carbon). Ambient measurements of same species.	Simple, no software needed. Indicates presence or absence of emitters. Inexpensive. Provides evidence of secondary PM formation and changes in source profiles between source and receptor.	Semi-quantitative. More useful for source/process identification than for quantification.

(continued)

Table 3.6 *continued*

Receptor Model	Model Requirements	Strengths	Limitations
Multi Linear Regression (MLR) CMB solution	100 or more samples with marker species measurements at a receptor. Minimal covariation among marker species due to common dispersion and transport.	Operates without source profiles. Abundance of marker species in source is determined by inverse of regression coefficient. Apportions secondary PM to primary emitters when primary markers are independent variables and secondary component (e.g. $SO_{4=}$) is dependent variable. Implemented by many statistical software packages.	Marker species must be from only the sources or source types examined. Abundance of marker species in emissions is assumed constant with no variability. Limited to sources or source areas with markers. Requires a large number of measurements.
Eigen Vector Analysis**	50 to 100 samples in space or time with source marker species measurements. Knowledge of which species relate to which sources or source types. Minimal co-variation among marker species due to common dispersion and transport. Some samples with and without contributing sources.	Intends to derive source profiles from ambient measurements and as they would appear at the receptor. Intends to relate secondary components to source via correlations with primary emissions in profiles. Sensitive to the influence of unknown and/or minor sources.	Most are based on statistical associations rather than a derivation from physical and chemical principles. Many subjective rather than objective decisions and interpretations. Vectors or components are usually related to broad source types as opposed to specific categories or sources.
Time Series	Sequential measurements of one or more chemical markers. 100s to 1000s of individual measurements.	Shows spikes related to nearby source contributions. Can be associated with highly variable wind directions. Depending on sample duration, shows diurnal, day-to day, seasonal, and inter-annual changes in the presence of a source.	Does not quantify source contributions. Requires continuous monitors. Filter methods are impractical.
Aerosol Evolution	Emission locations and rates. Meteorological transport times and directions. Meteorological conditions (e.g., wet, dry) along transport pathways.	Can be used parametrically to generate several profiles for typical transport/ meteorological situations that can be used in a CMB.	Very data intensive. Input measurements are often unavailable. Derives relative, rather than absolute, concentrations. Level of complexity may not adequately represent profile transformations.

(continued)

Table 3.6 *continued*

Receptor Model	Model Requirements	Strengths	Limitations
Aerosol Equilibrium	Total (gas plus particle) $SO_{4=}$, NO_{3-}, NH_{4+} and possibly other alkaline or acidic species over periods with low temperature and relative humidity variability. Temperature and relative humidity.	Estimates partitioning between gas and particle phases for NH_3, HNO_3, and NH_4NO_3. Allows evaluation of effects of precursor gas reductions on ammonium nitrate levels.	Highly sensitive to temperature and relative humidity. Short duration samples are not usually available. Gas-phase equilibrium depends on particle size, which is not usually known in great detail. Sensitivity to aerosol mixing state not understood/quantified.

Source: John Watson, Desert Research Institute, USA.

** Includes PCA, FA, Empirical Orthogonal Functions (EOF), PMF, and UNMIX.

from the National Environmental Research Institute, Denmark, is a hybrid physical receptor model, which combines both branches of receptor models, CMB and Multivariate models. COPREM is based on the CMB model, which needs the composition profile of sources in advance, but incorporates the ability of multivariate mathematics to fit the chemical species in the source profiles.

The *Principal Components Analysis (PCA) algorithm* can be found in the general statistical program packages available on most computer systems. The most common assumption is on the number of factors to be used (Roscoe et al., 1982). The factors used in PCA are not always physically realistic, as negative values may appear among factor loadings and factor scores. Additionally, PCA results do not represent a minimum variance solution because the method is based on incorrect weighting by assuming unrealistic standard deviations for the variables in the data matrix. Furthermore, PCA is incapable of handling missing and below-detection-limit data often observed in some measurements in developing countries.

The *UNMIX modeling*, developed by Henry (2001), is one of the most useful receptor models, using the multivariate method. The principle of UNMIX is closely related to PCA. The UNMIX model takes a geometric approach that exploits the covariance of the ambient data. Simple two-element scatter plots of the ambient data provide a basis for understanding the UNMIX model. For example, a straight line and high correlation for Al versus Si can indicate a single source for both species (soil), while the slope of the line gives information on the composition of the soil source. In the same data set, iron may not plot on a straight line against Si, indicating other sources of Fe in addition to soil. More importantly, the Fe-Si scatter plot may reveal a lower edge. The points defining this edge represent ambient samples collected on days when the only significant source of Fe was soil. Success of the UNMIX model hinges on the ability to find these "edges" in the ambient data from which the number of sources and the source compositions are extracted. However the UNMIX may produce some negative results, which are meaningless, as is also the case for the PCA.

The *Potential Source Contribution Function (PSCF)* combines the aerosol data with air parcel backward trajectories to identify potential source areas and the preferred pathways that give rise to the observed high aerosol concentrations at the receptor point. For a receptor point and a region, PSCF describes the spatial distribution of probable geographical source locations, for example, on a gridded field, grid cells which have high PSCF values are the potential source area whose emissions can contribute to the levels observed

at the receptor (monitoring) site. For secondary pollutants, the high PSCF area may also include areas where secondary formation is enhanced.

In the previous four sections, commonly applied techniques for source apportionment were discussed. Before a source apportionment method is selected, based on the steps discussed in this Chapter, apportionment methodologies should be fully developed, made technically viable, available in the public domain, and ready for regulatory application. The resources required to apply a particular source apportionment system should be clearly understood. Also, it should be known how many people, how much time, and how much money is required to start and maintain an assessment of source contributions. Otherwise, it is unlikely that a regulatory or research program would be established with the amount of support needed to do the work correctly.

When designing a receptor-based study consideration should be given to collecting $PM_{2.5}$ (fine) and PM_{10} (coarse) samples in separate filters—in either Teflon or Nuclepore for elemental analysis utilizing XRF or ICP for the analysis. If factor analysis is to be used, at least 50 samples need to be collected for each size fraction. For chemical mass balance, the number of samples is not as important. Samples with low and high loading should be analyzed to gain an understanding of the sources impacting these episodes. As resources devoted to receptor-based source apportionment increase, carbonaceous aerosol sampling and analysis could be added. Additionally, more sampling sites and longer sampling programs could be added. Finally, developing local source profiles is also an important consideration as AQMS resources become available.

4 Source Apportionment Case Studies and Results

This Chapter presents case studies of source apportionment analyses including study details, results, and recommendations for cities in Asia, Africa, and Latin America. The purpose of this Chapter is to gain an understanding of the motivations behind and barriers to, the adoption of certain methodologies for source apportionment, and results and recommendations based on the apportionment. Table 4.1 presents the urban areas studied. For most of these areas, the case study serves an important need by allowing a better understanding of the characterization and sources of air pollution city-wide.

It is important to note that for these studies, choices made on the analysis techniques and methodologies, specific sampling periods and frequency, spatial resolution, and data accuracy must be considered in interpreting the data. Although the studies provide valuable information about a range of cities, they do not cover all locations and times, even within the same urban area. Cases where a more detailed analysis of the samples was done, lead to the classification of air sheds into groups with similar particulate composition and concentration, which helps suggest the primary sources and increases the value of the studies. This gives policy makers the opportunity to implement cost-effective strategies in controlling pollutant emissions.

During the process of evaluating the case studies, a questionnaire (presented in Annex 5) was prepared and administered to generate feedback from institutions working on source apportionment methodologies. At the same time, a full literature survey was conducted for similar studies. In Annex 7, references to publications on source apportionment in general and source apportionment studies in Africa, China, India, Latin America, and Bangladesh specifically are presented. Studies presented in this Chapter focus on developing country cities only. There are numerous studies conducted in the United States and Europe, which use more advanced samplers, filters, and analytical techniques.

This compilation of 13 case studies reviewed the findings from 17 urban areas. The results of these studies are presented here in unified tabular forms. Specifically, the tables summarize the receptor locations, study methods and study findings, and the source categories identified. From these tables, general observations and recommendations are made. These cases are

Table 4.1 Case Study Urban Areas

Regions	Urban Areas
East Asia and Pacific (EAP)	Shanghai, Beijing, Xi'an, Bangkok, Hanoi
South Asia Region (SAR)	Mumbai, Delhi, Kolkata, Chandigarh, Dhaka and Rajshahi
Africa	Cairo, Qalabotjha, Addis Ababa
Latin America and Caribbean (LAC)	Sao Paulo, Mexico City, Santiago

Source: Authors' calcualtions.

instructive in that they provide the equipment and analytical techniques utilized to apportion samples under different circumstances. Chapter 5 presents the findings from an additional urban area—Hyderabad.

Shanghai (China)

Results and Recommendations

For the receptor analysis, the project team developed source profiles representative of Shanghai, such as small or medium size boilers, metallurgy boilers, cement kilns, and dust on representative roads. Refer to Annex 3 for these source profiles.

Major conclusions from this study suggest that: (1) power plant (PP) boilers, small and medium size coal boilers are still important pollutant sources for metal elements of $PM_{2.5}$ in the city zone of Shanghai; (2) being a seashore city, a large portion of the sample represented marine sources with seasonal variations; and (3) in the central traffic zones, vehicle exhaust is a dominant source. Of the $PM_{2.5}$, secondary particulates (sulfates, nitrates, and ammonium) accounted for 30 percent of the samples. Figure 4.1 presents contributions of various sources for each of the seasons and the annual average. Some of the source contributions are combined for simplicity. For example, coal boilers, oil boilers, brick kilns, and cement are combined

Box 4.1 Shanghai, China Case Study

Study Source/Reference: [41]
Shanghai Academy of Environmental Science (SAES), Shanghai, China.

Funding Source:
Shanghai EPB (0.8 million RMB) & GE company (0.5 million RMB).

Measurement Timeframe:
One-month continuous monitoring in October, January, April and June during 2000-2001, representing $PM_{2.5}$ pollution in autumn, winter, spring and summer. The total number of (usable) samples are 400–4 seasons, 7 sites, 15 samples per season (sampled only for one month in each season).

Site Characterization:
Baoshan (industrial), Shangshida and Pudong (residential), Hainan (road), Nanhui (background), Yangpu (old industrial), and Jingan (residential)

Sampling Equipment: High volume $PM_{2.5}$ samplers and middle volume $PM_{2.5}$ samplers.

Filter Types: Quartz filter for organic carbon (OC)/ elemental carbon (EC) analysis and Teflon filters from Beijing for elemental analysis were used.

Chemical Analysis: ICP-AES and XRF were applied to test the concentration of 16 elements at Fudan University Shanghai.

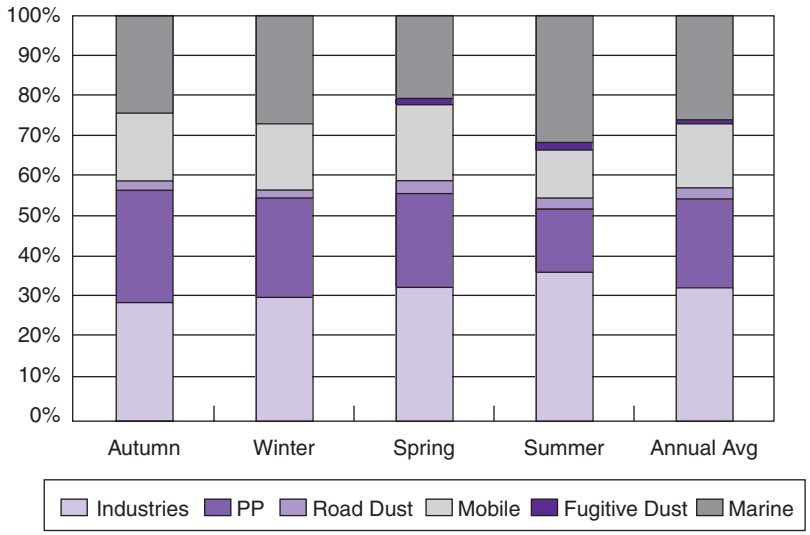
Receptor Model: CMB Model.

Measured Concentrations: Annual average $PM_{2.5}$ is 64.6 $\mu g/m^3$.

Source: Personal correspondence with Prof. Chenrong Chen, Director SAES, Email: saeschen2005@21cn.com (2005).

[41] Contact Information: Prof. Chenrong Chen, Director SAES, Email: saeschen2005@21cn.com.

Figure 4.1 Source Apportionment Results for Shanghai, China



Source: Personal correspondence with Prof. Chenrong Chen, Director Shanghai Academy of Environmental Science (2005).

under industries. In Shanghai, the results suggest that industry and power plants account for more than 50 percent of the $PM_{2.5}$ pollution, followed by marine (e.g., sea salt) sources.

This study was conducted with limited resources and focused only on elements and ions in $PM_{2.5}$ that occupy about 40 percent of the measured sample. The EC and OC part of the sample, which accounts for 25 percent of the sample, was not analyzed and was considered as total carbon. Further analysis of the carbon sample could result in more refined source apportionment results.

Beijing (China)

Results and Recommendations

Results shown in Figure 4.2 are from Song et al., 2006. This study employed organic molecular analysis for receptor modeling and also included PSCF analysis via back trajectory analysis for the period of April, 2000, which included a storm out of the Gobi desert. The PMF analysis conducted by the team captures that event. The figure also includes an annual average contribution of various sources. Average $PM_{2.5}$ concentrations greater than 160 $\mu g/m^3$ were measured during the dust storm period, which is 10 times the WHO guidelines.

Results suggest that the total contribution from secondary aerosols was the most substantial and accounted for more than 30 percent annually. These contributions likely result from coal and to a lesser degree petroleum product combustion in the city, which accounts for more than 50 percent of their energy supply and possible long range transport from neighboring cities. This long range transport also reduces the percent contribution of the local pollutants. The transportation sector and road dust account for only 15 percent compared to a total emission contribution of 44 percent of transport and fugitive dust from Figure 2.5. Similar studies were conducted by others in Beijing, (e.g., by groups such as the Chinese Research Academy of Environmental Sciences (CRAES)), which are not discussed here. Refer to Annex 7 for additional studies in China.

Box 4.2 Beijing, China Case Study

Study Source/Reference:
Department of Environmental Sciences, Peking University, Beijing, China.

Song et al., Atmospheric Environment Vol. 40 (2006) 1526–1537.

Zheng et al., Atmospheric Environment Vol.39 (2005) 3967–3976.

Funding Source: NA

Measurement Timeframe:
In January, April, July, and October 2000, $PM_{2.5}$ samples were collected in Beijing for 24 hr periods at five sampling sites simultaneously at 6-day intervals. Over 100 samples were collected in four months for analysis.

Site Characterization:
The five sampling sites include the Ming Tombs (OT), the airport (NB), Beijing University (BJ), Dong Si Environmental Protection Bureau (XY), and Yong Le Dian (CH).

Sampling Equipment: Two collocated dichotomous samplers at each site.

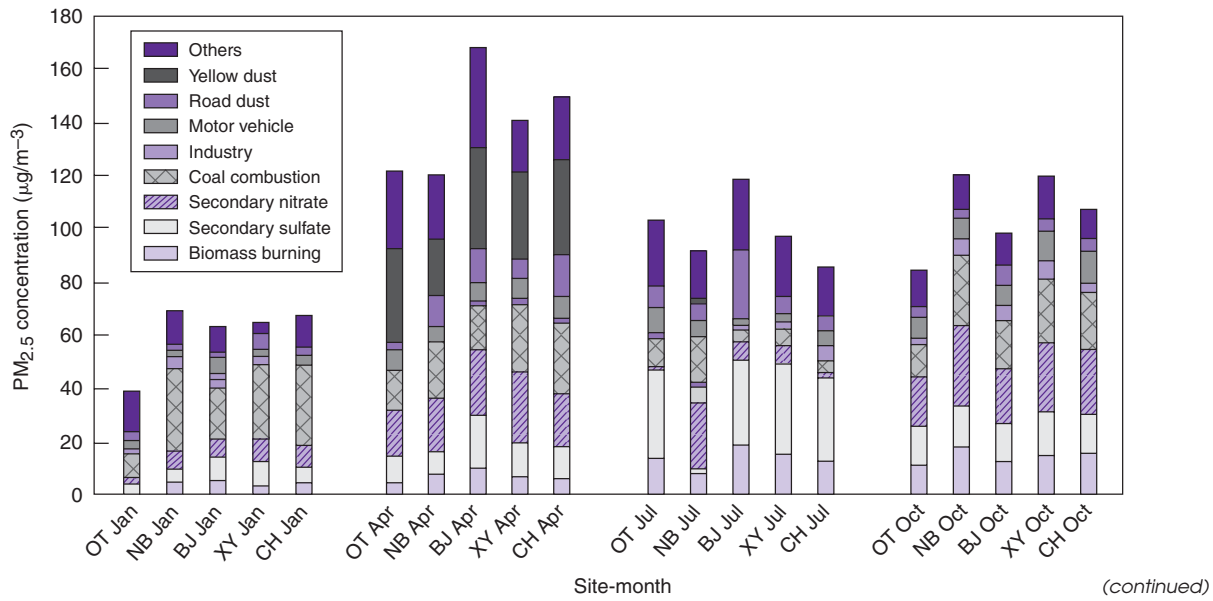
Filter Types: Mixed 37 mm diameter cellulose ester and quartz fiber filters. One sampler in the wet season 2002 collected samples on Teflon filters.

Chemical Analysis: For each sample, mass concentrations were obtained and the chemical composition was analyzed for ions by IC and for metals by XRF spectroscopy. The OC and EC were determined by U.S. National Institute for Occupational Safety and Health (NIOSH) thermal-optical procedures. The detailed organic speciation obtained monthly was ascertained by GC/MS.
Receptor Model: CMB7 (Zheng et al., 2005) and PMF (Song et al., 2006).

Measured Concentrations: Annual average $PM_{2.5}$ ranged from 100-140 μg/m^3.

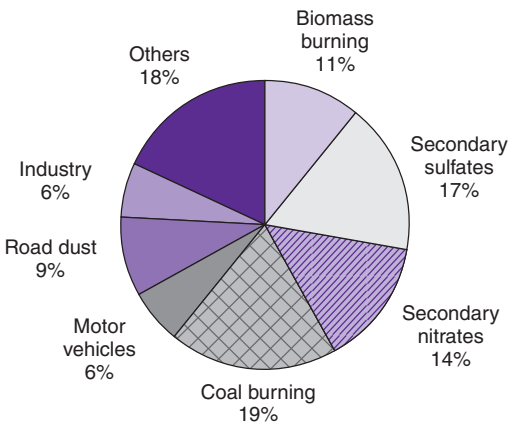
Source: Song et al., (2006) and Zheng et al., (2005).

Figure 4.2 Source Apportionment Results for Beijing, China



(continued)

Figure 4.2 *continued*



Source: Song et al. (2006).

Xi'an (China)

Results and Recommendations

This study also constructed source profiles for three main sources in Xi'an—coal combustion, motor vehicle exhaust, and biomass burning. EC and OC account for 45 and 75 μg/m^3 of $PM_{2.5}$ in fall and winter, respectively, which are above WHO guidelines. It should be noted that this study focused primarily on the carbon matter of the samples and does not include elemental analysis or ions (non-carbonaceous) which accounts for more than 50 percent of the $PM_{2.5}$ in parts of China. Clearly, the results suggest that the transportation sector is dominating—gasoline and diesel—in fall and winter seasons.

Box 4.3 Xi'an, China Case Study

Study Source/Reference:
Chinese Academy of Sciences, Xi'an, China

Cao et al., Atmospheric Chemistry and Physics Vol. 5, (2005) 3561-3593.

Funding Source: NA

Measurement Timeframe:
PM samples were collected during fall (13 September 2003 to 31 October 2003) and winter (1 November 2003 to 29 February 2004). $PM_{2.5}$ was sampled everyday and PM_{10} once every three days.

Site Characterization:
$PM_{2.5}$ and PM_{10} samples were obtained from the rooftop of the Institute of Earth Environment, Chinese Academy of Sciences, at 10 m above ground level.

Sampling Equipment: MiniVol™ samplers.

Filter Types: pre-fired quartz-fiber filters.

Chemical Analysis: Ambient and source samples were analyzed for OC and EC by thermal/optical reflectance (TOR) following the Interagency Monitoring of Protected Visual Environments (IMPROVE) protocol.

Receptor Model: Absolute Principal Component Analysis (APCA).

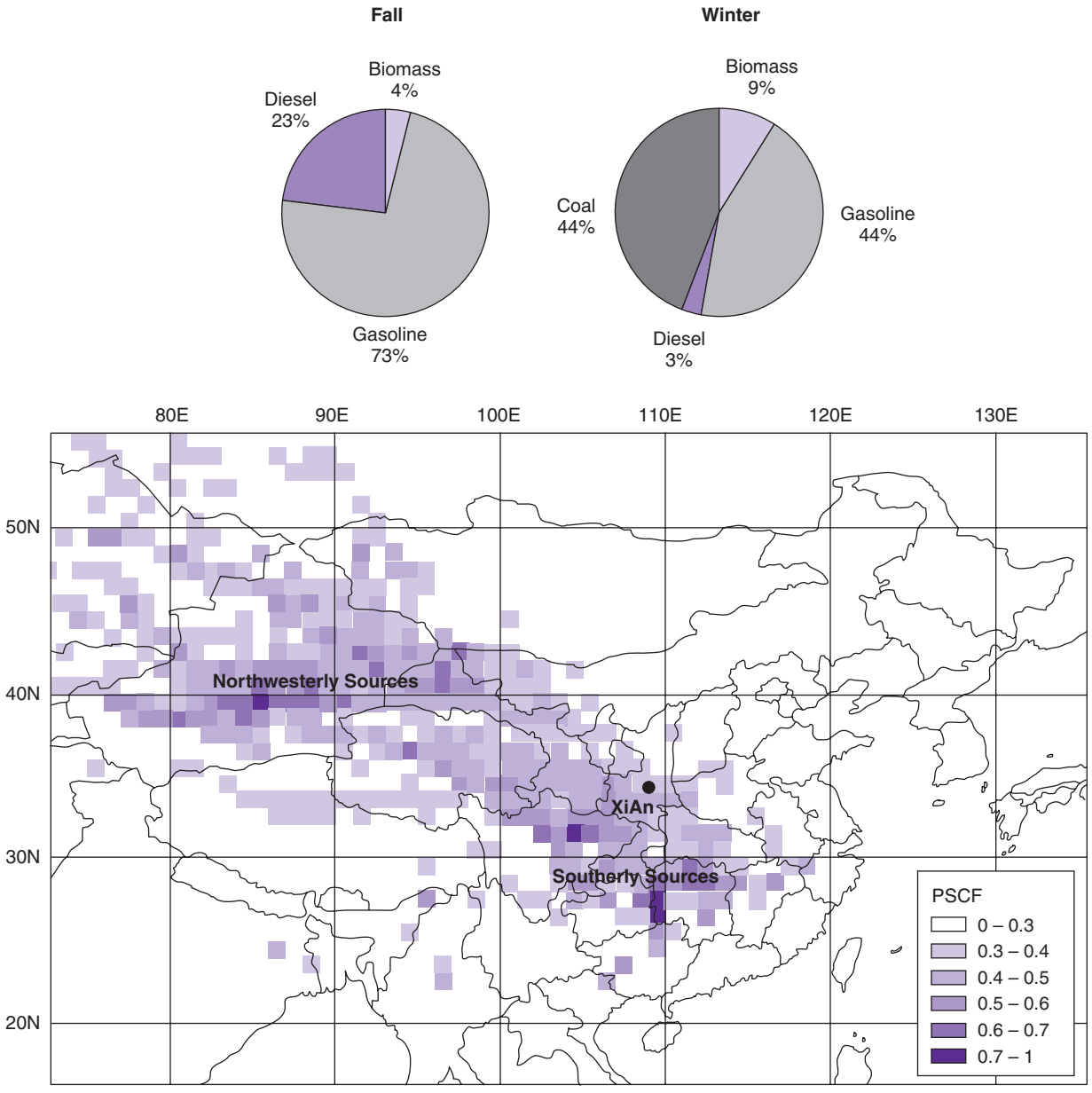
Measured Concentrations: The average $PM_{2.5}$ OC concentrations in fall and winter were 34.1±18.0 μg/m^3, and 61.9±33.2 μg/m^3, respectively, while EC were 11.3±6.9 μg/m^3 and 12.3±5.3 μg/m^3, respectively.

Source: Cao et al., (2005).

Coal use for heating in the winter contributes 44 percent of the carbonaceous sample, which clearly needs attention.

For a city like Xi'an, which is inland surrounded by booming provinces, inter-provincial long range transport of air pollution also contributes to local air quality. Wang et al., 2006, studied source apportionment using the PSCF method by drawing back trajectories from Xi'an (for Spring of 2001 and 2003) and identifying potential source regions contributing to the city's air quality. Besides dust sources from the Gobi and Taklimakan deserts, one anthropogenic source was identified which encompasses the northern part of Sichuan Province and northern and western parts of Hunan Province. Results such as these provide local authorities evidence

Figure 4.3 Source Apportionment Results for Xi'an, China



Source: Wang et al., (2006).

Note: Darker colors in map indicate greater source area potential.

that can be used when pressing regional and/or national authorities for stricter emissions standards outside the governing authority's jurisdiction.

Bangkok (Thailand)

Results and Recommendations

Major conclusions suggested by this study are: the biomass burning contribution to $PM_{2.5}$ was very high during the dry season, which is accounted for by the high amounts of rice straw openly burned in the Bangkok Metropolitan Region during the dry season; Fine particulate pollution is dominated by the secondary particulates (mainly sulfates), biomass burning, and motor vehicles; and Coarse PM was dominated by soil dust and construction activities.

This study was conducted as part of the Asian regional air pollution research network (AIRPET), which is funded by the Swedish International Development Cooperation Agency (Sida) and coordinated by the Asian Institute

Box 4.4 Bangkok, Thailand Case Study

Study Source/Reference: [42]
Asian Institute of Technology (AIT), Bangkok, Thailand. This experiment was conducted as part of the Asian regional air pollution research network (AIRPET) regional project.

Funding Source:
US$200,000, Swedish International Development Agency (Sida) is the main sponsor.

Measurement Timeframe:
Samples were collected from Feb. 2002 to the end of 2003 and covered both dry and wet seasons. Bang Na and AIT are the intensive sites with more than 50 samples at each site. At other sites the sample number varies from 20 to 30+.

Site Characterization:
Bang Na is mixed urban-industrial, Ban Somdej is an urban residential, Dindang as a traffic site (3 m from traffic lane), Bangkok University as semi urban (35 km upwind of Bangkok city center).

Sampling Equipment: Two collocated dichotomous samplers.

Filter Types: Mixed 37 mm diameter cellulose ester and quartz fiber filters. One sampler in the wet season 2002 collected samples on Teflon filters.

Chemical Analysis: PIXE and XRF. XRF was used for Teflon filters; Gravimetric PM mass measurement at AIT; Ion chromatography for inorganic ions at the Pollution Control Department (PCD), Bangkok; PIXE method for elemental analyses at National Environmental Research Institute, Denmark; and Reflectometer for black carbon (BC) at AIT. Samples were collected on Quartz filters. One part was analyzed for EC/OC by NIOSH method at the UC-Davis laboratory, a part was analyzed for ions by IC and a part was analyzed for PAH.

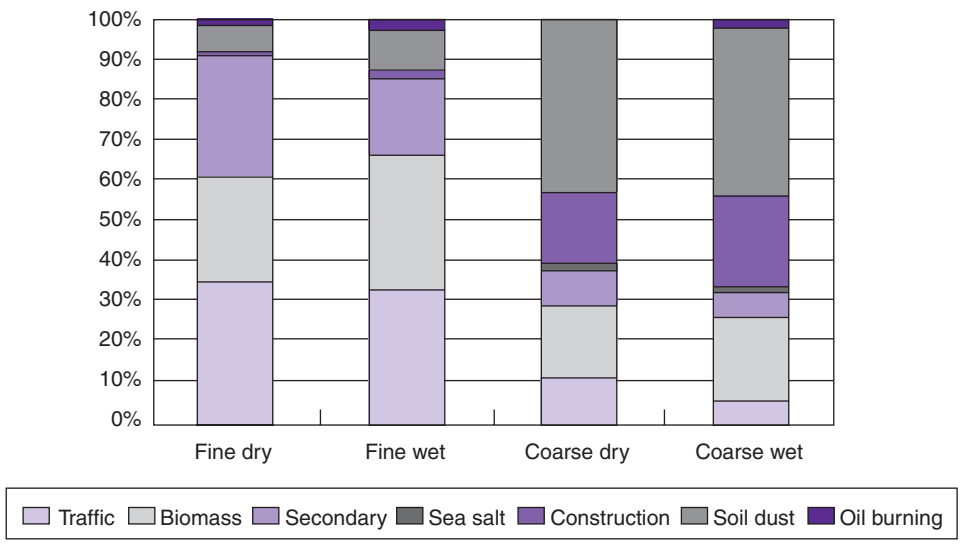
Receptor Model: CMB Model.

Measured Concentrations: 24-hr average $PM_{2.5}$ ranged from 36-81 $\mu g/m^3$.

Source: Personal correspondence with Prof. Kim Oanh, Asian Institute of Technology, Bangkok, Thailand. Email: kimoanh@ait.ac.th (2005).

[42] Prof. Kim Oanh, Asian Institute of Technology, Bankok, Thailand. Email: kimoanh@ait.ac.th.

Figure 4.4 Source Apportionment Results for Bangkok, Thailand



Source: Kim Oanh, 2004 visit to WB. Fine is $PM_{2.5}$ and Coarse is $PM_{2.5–10}$.

of Technology. AIRPET, now in phase 2, has as one of its main research objectives providing a comprehensive assessment of PM pollution. The focus is on $PM_{2.5}$ and $PM_{10}/PM_{10–2.5}$ levels and composition with the spatial and temporal distribution in six cities/metropolitan regions in Asia, namely, the Bangkok Metropolitan Region (BMR, Thailand), Bandung (Indonesia), Beijing (China), Chennai (India), Metro Manila Region (Philippines), and Hanoi Metropolitan Region (Vietnam). More details of the program can be obtained from http://www.serd.ait.ac.th/airpet.

Hanoi (Vietnam)

Results and Recommendations

This study combined PMF and PSCF methods to evaluate the contribution of local and long range transport (LRT) pollution. In the fine mode, results suggest LRT contributes the most followed by local fossil fuel burning while the local burning and soil dust (fugitive dust) dominate in the coarse mode. Three thermal power stations in northern Vietnam consume more than 1.5 million tons of coal annually, which is accounted in the long range transport.

The study does not distinguish between sectors (other than motor vehicles) or fuels for estimating local burning and this is likely to include some more of the transportation emissions. Coal is widely used for cooking in the city and for producing bricks and pottery in the suburban areas. The major fuel used in rural areas is lumber and crop residues, the latter accounts for more than 50% of energy consumption in the delta area of North Vietnam. The most popular transportation means for Hanoi residents is the motor-scooter. Up to 2001 more than 1.5 million scooters and 110,000 cars were registered in the Hanoi municipality, which accounts for most of the ground level air pollution from the transportation sector.

Box 4.5 Hanoi, Vietnam Case Study

Study Source/Reference:
Vietnam Atomic Energy Commission, Hanoi, Vietnam.

Hien et al., Atmospheric Environment Vol. 38, (2004) 189–201.

Funding Source: NA.

Measurement Timeframe:
1999–2001.

Site Characterization:
$PM_{2.5}$ and PM_{10} samples were obtained from the rooftop of the Institute of Earth Environment, Chinese Academy of Sciences, at 10m above ground level.

Sampling Equipment: Gent Stacked Filter Samplers.

Filter Types: 47mm diameter Nuclepore polycarbonate filters.

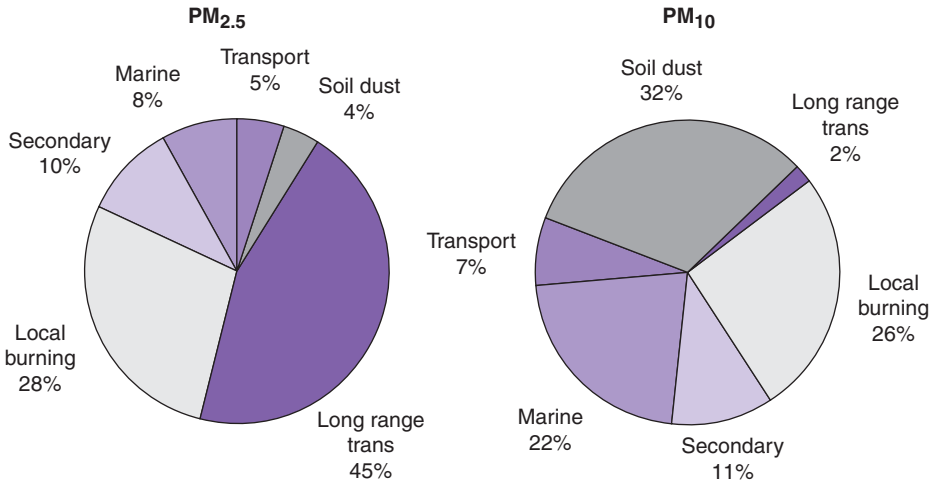
Chemical Analysis: Ion chromatography (IC) and reflectance method were used for analyzing for water soluble ions and black carbon (BC) in air samples, respectively.

Receptor Model: PMF and PSCF.

Measured Concentrations: The average $PM_{2.5}$ for the sampling period is 103 μg/m^3

Source: Hien et al., (2004).

Figure 4.5 Source Apportionment Results for Hanoi, Vietnam



Source: Hien et al., (2004).

Note: Results above are the average of three stages presented in the paper.

Cairo (Egypt)

Results and Recommendations

For this analysis, DRI also sampled source profiles for bulk soil and road dust at each of the ambient-sampling sites. Emissions from various sources including brick manufacturing, cast iron foundry, copper foundry, lead smelting, refuse burning, Mazot oil combustion, refuse burning, and restaurants were sampled. Individual motor vehicle emissions were sampled from heavy- and light-duty diesel vehicles, spark ignition automobiles, and motorcycles. Figure 4.6 presents suggested shares of various sources to PM_{10} and $PM_{2.5}$ ambient levels. Major contributors to PM_{10} included geological material, mobile source emissions, and open burning. $PM_{2.5}$ tended to be dominated by mobile source emissions, open burning, and secondary species.

Depending on the sites, major contributors to PM_{10} included geological material, mobile source emissions, and open burning. $PM_{2.5}$ tended to be dominated by mobile source emissions, open burning, and secondary species. Aside from the extremely high mass levels, two unusual features emerged. First, most sites had high levels of ammonium chloride during the two 1999 sampling periods. Second, lead concentrations were very high during the winter 1999 sampling period at Shobra. Eighty percent of the lead contribution was in the $PM_{2.5}$ fraction. Most of this lead was in the form of fresh emissions from secondary smelters in the vicinity.

Box 4.6 Cairo, Egypt Case Study

Study Source/Reference:[43]
Desert Research Institute, Reno, Nevada U.S.A.

Abu-Allban et al., Atmospheric Environment Vol. 36 (2002) 5549-5557.

Funding Source:
U.S. Agency for International Development (USAID) and the Egyptian Environmental Affairs Agency (EEAA) supported the Cairo Air Improvement Project (CAIP).

Measurement Timeframe:
Intensive monitoring studies were carried out during the periods of February/March and October/November 1999 and June 2002.

Site Characterization:
Kaha, a Nile delta site for background, Shobra El-Khaima and El Massara for mixed industrial and residential, El Qualaly Square, a site located downtown for traffic, Helwan and El-Zamalek for residential.

Sampling Equipment: MiniVol™ Samplers.

Filter Types: Teflon-membrane and quartz-fiber filters.

Chemical Analysis: XRF, IC and TOR.

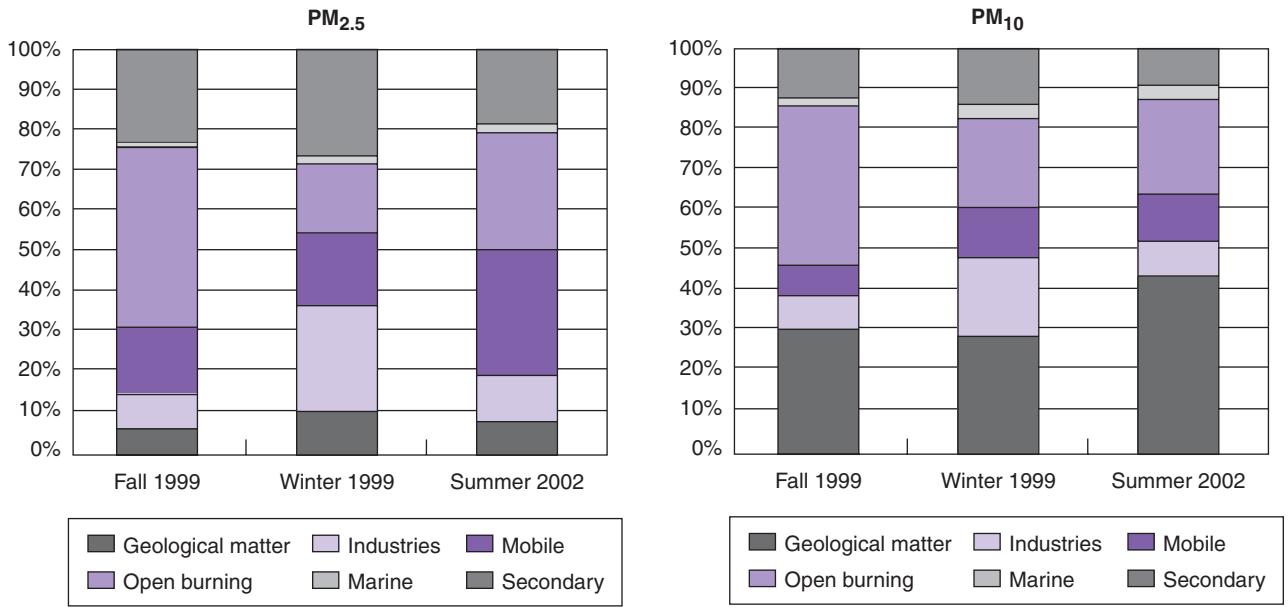
Receptor Model: CMB Model.

Measured Concentrations: For the measurement periods concentrations averaged 265 µg/m^3, 163 µg/m^3, and 134 µg/m^3 for PM10 and 127 µg/m^3, 84 µg/m^3, and 48 µg/m^3 for $PM_{2.5}$ for Fall 1999, Winter 1999 and Summer 2002, respectively.

Source: Personal correspondence with Dr. Alan Gertler, Desert Research Institute, Reno, Nevada, USA and Abu-Allban et al., (2002).

[43] Contact Information: Dr. Alan Gertler, DRI, Reno, USA. Email: Alan.Gertler@dr.edu.

Figure 4.6 Source Apportionment Results for Cairo, Egypt



Source: Abu-Allban et al., (2002).

Based on the receptor modeling study, major recommendations included implementation of programs to reduce area source emissions—geological matter and road dust, implementation of a comprehensive enforcement program to ensure industrial compliance with air quality regulations—especially for the lead smelters, development of policies to encourage retrofitting existing industrial sources with lower emitting technologies.

Qalabotjha (South Africa)

Results and Recommendations

Chemical source profiles for low-smoke fuels, local soils, vegetative burning were measured as part of this project. Previously chemical source profiles of industrial processes in the Vaal Triangle had been measured, including a coal fired power plant, steel industry, and cement plant.

This study was conducted exclusively for policy decisions on energy use in Qalabotjha, to convince authorities to subsidize electrification of townships (low-grade coal is by far the cheapest form of energy in South Africa). The source apportionment study found that residential coal combustion is 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 sites, followed by biomass burning for 14 and 20 percent, respectively. Fugitive dust is only significant in the coarse particle fraction, accounting for 11.3 percent of PM_{10}. Contributions from secondary ammonium sulfate are three–four times greater than from ammonium nitrate, accounting for 5–6 percent of PM mass, sulfates primarily originated from residential coal combustion.

Box 4.7 Qalabotjha, South Africa Case Study

Study Source/Reference:[44]
Desert Research Institute, Reno, Nevada, U.S.A.

Engelbrecht, et al., Environmental Science & Policy Vol. 5. (2002) 157–167.

Funding Source:
US$150,000 multiple agencies.

Measurement Timeframe:
Samples collected every day for 24 hours. Samples taken during midwinter in July, 1997. Samplers on roof-tops of buildings.

Site Characterization:
Three ambient sites in black township represent residential coal combustion and other activities (road transport). One background site in Villiers, an adjacent white residential area.

Sampling Equipment: MiniVol™ Samplers.

Filter Types: Teflon-membrane and quartz-fiber filters.

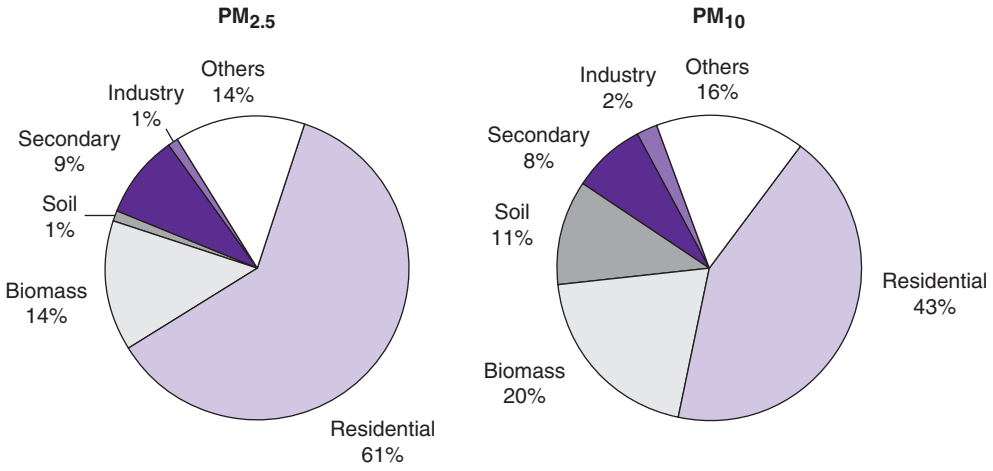
Chemical Analysis: XRF, IC and TOR.

Receptor Model: CMB Model.

Measured Concentrations: $PM_{2.5}$ was 113 µg/m^3 and PM_{10} was 124 µg/m^3

Source: Engelbrecht, et al., (2002).

Figure 4.7 Source Apportionment Results for Qalabotjha, South Africa



Source: Engelbrecht, et al., (2002).

Addis Ababa (Ethiopia)

Results and Recommendations

This is an on-going study. As a result the available analysis is limited. Although not comprehensive, the list of air pollution sources includes light and heavy-duty motor-vehicles, industry, home heating and cooking, as well as fugitive sources such as biogenic emissions and dust. Chemical source profiles for low-smoke fuels, local soils, vegetative burning were measured as part of this project.

Preliminary results suggest 35–65 percent of the PM_{10} was of geologic origin and

[44] Contact Information: Dr. Johann P. Engelbrecht, DRI, Reno, U.S.A. Email: johann@dri.edu.

Box 4.8 Addis Ababa, Ethiopia Case Study

Study Source/Reference:[45]
Desert Research Institute, Reno, Nevada, U.S.A.
Etyemezian et al., Atmospheric Environment Vol.39 (2005) 7849-7860.

Funding Source:

Measurement Timeframe:
Twenty-one samples were collected during the dry season (26 January-28 February 2004) at 12 sites in and around Addis Ababa for PM_{10}

Sampling Equipment: MiniVol™ Samplers.

Filter Types: Teflon-membrane and quartz-fiber filters.

Chemical Analysis: XRF, IC and TOR.

Receptor Model: CMB Model.

Measured Concentrations: PM_{10} concentrations ranged from 35 µg/m^3 to 87µg/m^3

Source: Etyemezian et al., (2005).

probably due to paved and unpaved road dust, and 35–60 percent due to organic matter and elemental carbon. Because Addis Ababa is not highly industrialized, the sources of carbon that are important on the urban scale are limited to gasoline and diesel vehicles, as well as biomass burning for residential heating and cooking.

Study recommendations include a proposal for multi-year study, or permanent monitoring station, which would provide better assessment of the long-term temporal trends. Due to use of biomass in poorly ventilated areas for home heating and cooking, indoor air pollution is a more critical problem than outdoor pollution in this region and needs immediate attention. This study is the first of its kind in Ethiopia and such analysis could be useful for economical placement of controls on air pollution.

Dhaka and Rajshahi (Bangladesh)

Results and Recommendations

Major emission sources in Dhaka are motor vehicles; re-suspended dust particles, biomass/coal burning in brick kilns and cooking, and other anthropogenic activities (medium, small and informal industries such as metal smelter, plastic industry, leather industry, etc). Source profiles were characterized for these sources.

From the available source apportionment studies, it is observed that the following sources have significant strength to contribute to high concentration of PM in ambient air in Dhaka during the dry season—vehicular emissions, particularly motor cycles, diesel trucks and buses (most dominant of the sources in both fine and coarse mode); soil and road dusts arising from civil construction and broken roads and open land surface; biomass burning in brickfields and city incinerators (to the fine mode). A cluster of more than 700 brick kilns lie north of Dhaka contributing much of the fine PM pollution in the dry season. Growing construction activity (also contributing to the fugitive dust) is the leading demand source for brick kilns and burning of biomass and low quality coal for brick making.

Similar procedures and methodologies are being developed for other Bangladeshi cities, e.g., Rajshahi, Chittagong and Khulna. Preliminary work is being conducted at Rajshahi station. The results are presented below. The work in the other two cities is in

[45] Contact Information: Dr. V. Etyemezia, DRI, Reno, U.S.A. Email: vic@dri.edu.

Box 4.9 Dhaka and Rajshahi, Bangladesh Case Study

Study Source/Reference:[46]
Bangladesh Atomic Energy Center, Dhaka, Bangladesh.

Funding Source:
US$16,000 for equipment, not including personnel.

Measurement Timeframe:
Sampling began in 1993. On an average 100 samples per year. Samples collected every 24 hrs. The samples for this study were collected during June 2001 to June 2002 in Dhaka and August 2001– May 2002 in Rajshahi.

Site Characterization:
Farm gate (Hot Spot—Near a road junction) and Atomic Energy Centre, Dhaka (Semi-residential area) in Dhaka and a background station in Savar (20 km North of Dhaka).

Sampling Equipment: 'GENT' stacked filter samplers.

Filter Types: Neuclepore polycarbonate filters.

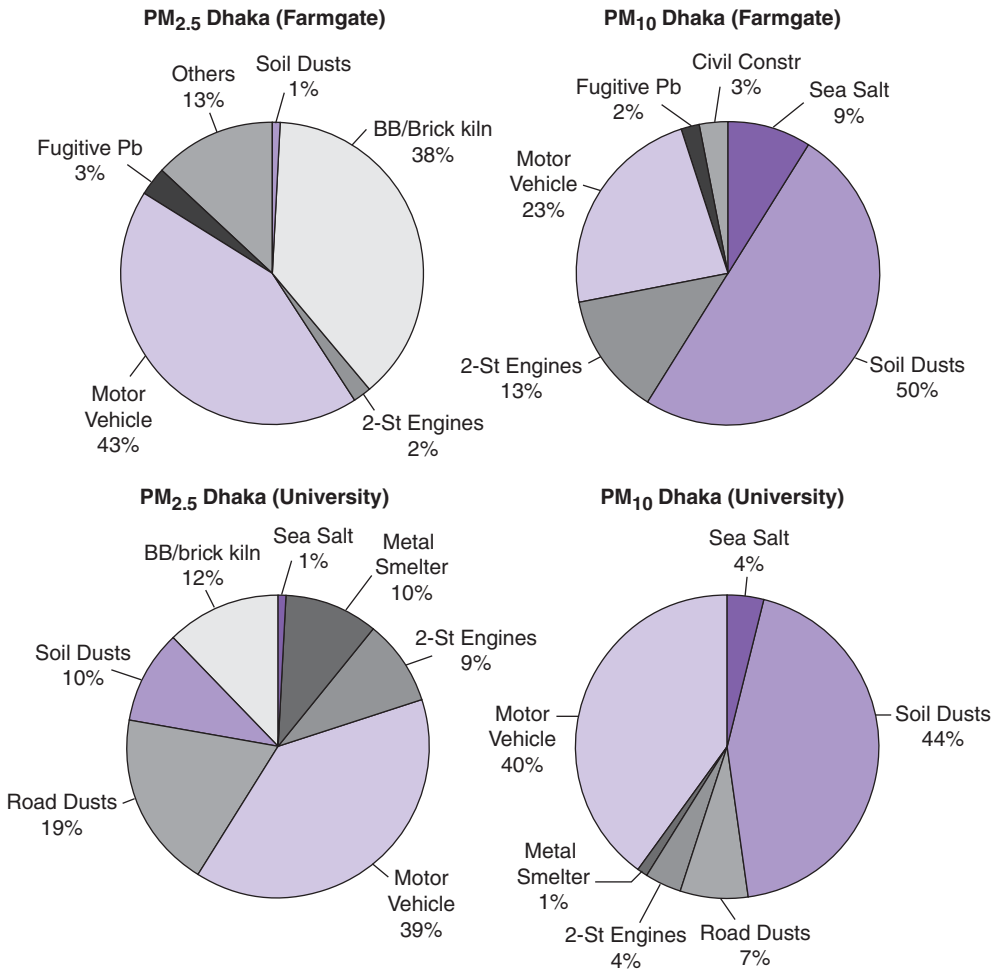
Chemical Analysis: PIXE.

Receptor Model: PMF.

Measured Concentrations: $PM_{2.5}$ averaged 113 μg/m^3 and PM_{10} averaged 124 μg/m^3

Source: Personal correspondence with Dr. Swapan K. Biswas, BAEC, Dhaka, Bangladesh. Email: sbiswas@baec.org.bd (2005).

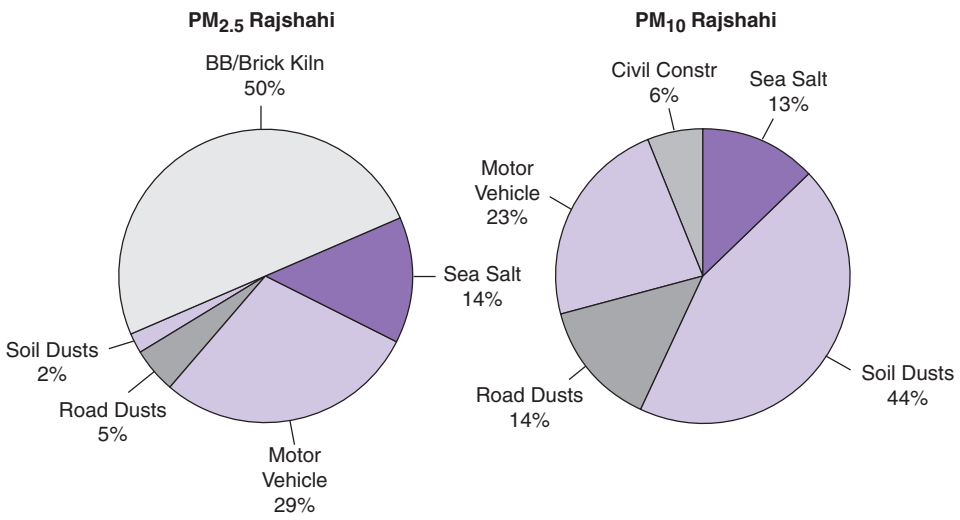
Figure 4.8 Source Apportionment Results for Dhaka, Bangladesh



Source: Personal correspondence with Dr. Swapan K. Biswas, BAEC, Dhaka, Bangladesh. Email: sbiswas@baec.org.bd (2005).

[46] Contact Information: Dr. Swapan K. Biswas, BAEC, Dhaka, Bangladesh. Email: sbiswas@baec.org.bd.

Figure 4.9 Source Apportionment Results for Rajshahi, Bangladesh



Source: Personal correspondence with Dr. Swapan K. Biswas, BAEC, Dhaka, Bangladesh. Email: sbiswas@baec.org.bd (2005).

initial stages. Similar to Dhaka, the results suggest the brick kiln industry dominates the fine PM pollution in Rajshahi.

Delhi, Kolkata, Mumbai, Chandigarh (India)

Results and Recommendations

This study, the first of its kind conducted in India, applied a molecular marker source apportionment model on the measured organic carbon from the four sampling sites, which gives more detailed information compared to receptor analysis of elements and ions of the measured samples. In this work, the particles were analyzed for organic carbon, graphitic carbon, metals, and ions, and the hydrocarbons found in organic carbon were further subjected to detailed speciation. The results from the hydrocarbon speciation were then used for identifying five sources of fine particle air pollution using chemical mass balance modeling—diesel exhaust, gasoline exhaust, road dust, coal combustion, and biomass combustion.

Important trends in the seasonal and spatial patterns of the impact of these five sources were observed. The summer monsoonal trends were captured in the measurements followed by highest levels of fine particulates were measured in winter. Proximity to the ocean and the influence of diurnal land and sea breezes aid in the dilution of the aerosol concentration seen in both Mumbai and Kolkata since ocean air is cleaner than continental air. On the other hand, inland Delhi experienced high concentrations throughout the year. Primary emissions from fossil fuel combustion (coal, diesel, and gasoline) were 22-33% in Delhi, 23-29% in Mumbai, 37-70% in Kolkata, and 24% in Chandigarh. These figures are comparable to the biomass combustion of 9-28% for Delhi, 12-21% for Mumbai, 15-31% for Kolkata, and 9% for Chandigarh, and this biomass includes fuels used for cooking and possibly waste burning.

One of the major limitations of this work contributing to large uncertainties in the results are the lack of regional source profiles and the lack of a statistically significant number of samples for each season. There is a need to conduct several source tests for diesel and gasoline combustion using vehicles representing the local vehicle fleet (diesel trucks, three-wheel auto-rickshaws). Coal

Box 4.10 Delhi, Kolkata, Mumbai, and Chandigarh, India Case Study

Study Source/Reference: [47]
Georgia Institute of Technology, Atlanta, Georgia, U.S.A.

Funding Source:
Total Project cost is US$150,000.

The World Bank: US$35,000; Georgia Institute of Technology: US$105,000; and Georgia Power Prof. Funds: US$10,000.

Measurement Timeframe:
Samples were collected for 24 hours, every sixth day for one month during each of the four seasons of 2001 in Delhi, Mumbai, and Kolkata. The selected four months were: March (spring), June (summer), October (autumn), and December (winter). In Chandigarh, samples were collected only during summer.

Site Characterization:
Site locations in Mumbai, New Delhi, and Kolkata are considered urban residential and Chandigarh as rural residential and as a background site upwind of New Delhi.

Sampling Equipment: Caltech built, $PM_{2.5}$ filter sampler.

Filter Types: $PM_{2.5}$ was collected on one quartz fiber filter (Pallflex, 2500 QAO, 47 mm diameter), on two pre-washed Nylon Filters (Gelman Sciences, Nylasorb, 47 mm diameter), and on two PTFE filters (Gelman Sciences, Teflon, 1.0 μm pore size).

Chemical Analysis: XRF, IC, GCMS, Carbon Analyzer and Gravimetric.

Receptor Model: CMB Model.

Measured Concentrations: For the period studied, average fine particle mass concentrations during the winter season were: Delhi , 231±1.6 μg m^{-3}; Mumbai 89±0.54 μg m^{-3}, and Kolkata 305±1.1 μg m^{-3} and average fine particle mass concentration during the summer were: Delhi, 49±0.64 μg m^{-3}; Mumbai, 21±1.4 μg m^{-3}, and Kolkata, 27±0.45 μg m^{-3}

Source: Prof. Armistead G. Russell, Georgia Institute of Technology, Atlanta, USA. Email: ted.russell@ce.gatech.edu.

source tests using Indian and Bangladeshi coal were conducted. However, organic speciation work was not concluded. Emissions from local soil profiles (paved road dust as well as non-paved road dust) are necessary to refine the results from this work.

Finally, it is important to reconcile the observations and source apportionment work done here with results that would be achieved using a source-based/bottom-up model in order to evaluate the emission inventories developed for the various regions. Magnitude of calculation for Mumbai suggests that the two will give consistent results, though may differ quantitatively. This latter work is important for identifying possible missing sources and to provide a defensible approach to policy-makers that can directly link specific sources to their air quality and health impacts.

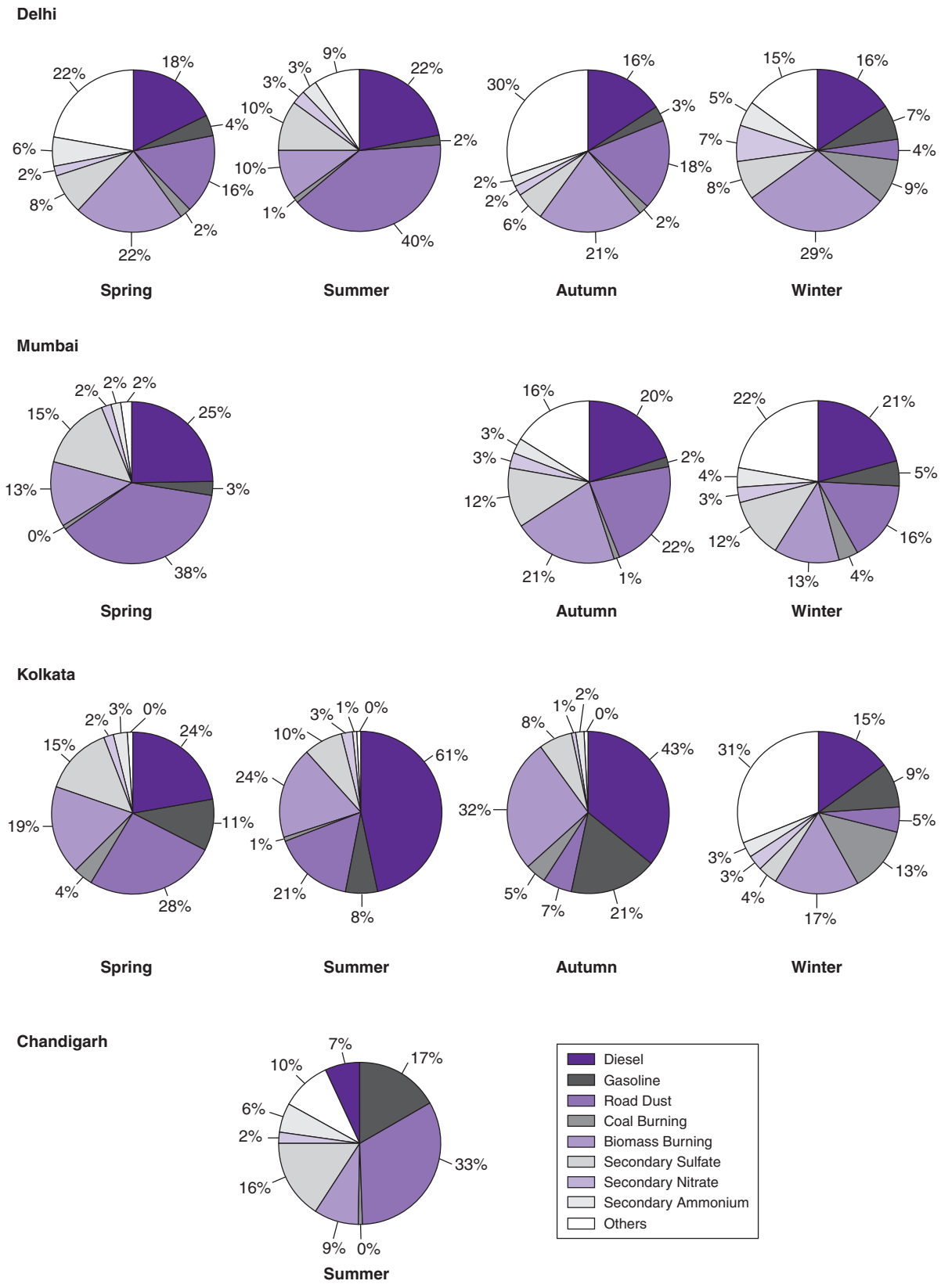
Sao Paulo (Brazil)

Results and Recommendations

The strong emissions of trace gases and aerosol by vehicles, industry, and the lack of rain that favors high resuspension of soil dust, under the unfavorable natural conditions of dispersion, contribute significantly to the high concentrations of pollutants observed in the entire region. Figure 4.12 presents source apportionment results for PM2.5 samples. The

[47] Contact Information: Prof. Armistead G. Russell, Georgia Institute of Technology, Atlanta, U.S.A. Email: ted.russell@ce.gatech.edu.

Figure 4.10 Source Apportionment Results for Four Cities in India



Source: Prof. Armistead G. Russell, Georgia Institute of Technology, Atlanta, U.S.A. Email: ted.russell@ce.gatech.edu.

Box 4.11 Sao Paulo, Brazil Case Study

Study Source/Reference:[48]
University of Sao Paulo (USP), Brazil.

Funding Source:

Measurement Timeframe:
Two sampling campaigns were carried out continuously during the wintertime of 1997 (June 10th until September 10th) and summertime of 1998 (January 16th until March 6th).

Site Characterization:
The wintertime study was carried out in a site located about 6 km from downtown São Paulo at the Medical School building at the USP. The summertime campaign was carried out 10 km from downtown, in a mostly residential region.

Sampling Equipment: Stacked Filter Units.

Filter Types: 47 mm Nuclepore polycarbonate filters, in two separated size fractions.

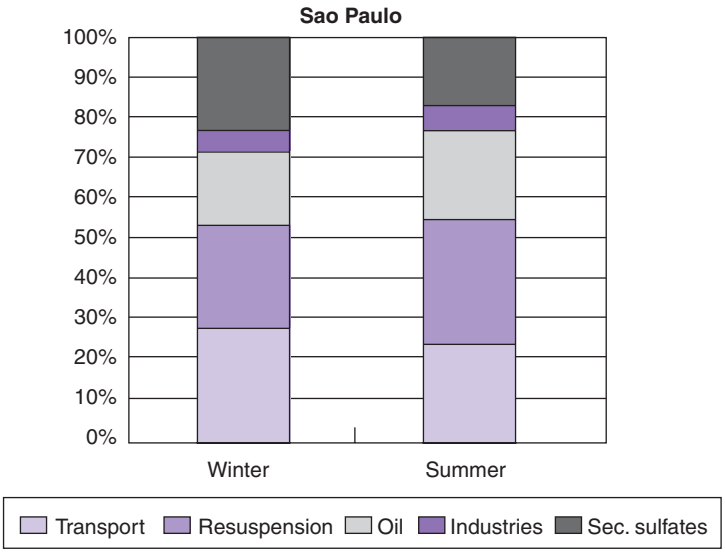
Chemical Analysis: PIXE, TEOM®

Receptor Model: Absolute Principal Factor Analysis (APFA).[49]

Measured Concentrations: For winter period, average PM_{10} was 77 μg/m³ with highs ranging between 20 μg/m³ and 160 μg/m³; For the summer period average PM_{10} was 32 μg/m³ with highs ranging between 20 μg/m³ and 80 μg/m³. The average $PM_{2.5}$ during wintertime was 30 μg/m³ and 15 μg/m³ during summertime.

Source: Prof. Paulo Artaxo, University of Sao Paulo, Brazil. Email: artaxo@if.usp.br.

Figure 4.11 Source Apportionment Results for Sao Paulo, Brazil



Source: Prof. Paulo Artaxo, University of Sao Paulo, Brazil. Email: artaxo@if.usp.br.

[48] Contact Information: Prof. Paulo Artaxo, University of Sao Paulo, Brazil. Email: artaxo@if.usp.br.

[49] The APFA is a variant of principal factor analysis discussed in Chapter 3. APFA simplifies the representation of the receptor data (Chan and Mozurkewich, 2007).

main difference between winter and summer periods is in the absolute concentration of the particulate mass that is significantly higher during the winter, when the meteorological conditions for dispersion of the pollutants are frequently more unfavorable. The analyses of the particulate mass balance showed that the organic carbon (40±16%) represents a large fraction of the fine particulate matter, followed by black carbon (21±4%) and sulfates (20±10%) and for the soil component (12±2 %).

The resuspended soil dust accounted for a large fraction (75-78%) of the coarse mode, which is also related to the transportation sector. From Figure 2.5, road dust and the transportation sector accounted for 53 percent of the PM_{10} emissions. Note that the sampling period is from 1997 to 1998 and emissions are from year 2002. Nevertheless, this fact indicates the importance of low lying sources such as road dust and their influence on ambient levels. The sampling campaigns carried out in the winter and summer periods resulted in similar aerosol source apportionments despite the fact that they were carried out in two different sampling sites, with transportation (along with resuspension of road dust) accounting for 50 percent of the measured $PM_{2.5}$ mass.

Mexico City (Mexico)

Results and Recommendations

This study also conducted PSCF analysis using back trajectories for the experimental period, presented in the Figure 4.13. Wind trajectories suggest that industrial emissions came from large northern point sources, whereas soil aerosols came from the southwest and increased in concentration during dry conditions. Elemental markers for fuel oil combustion, correlated strongly with a large SO_2 plume to suggest an anthropogenic, rather than volcanic, emissions source. The study did not classify the contribution of the transportation sector. A large portion of sulfates in the sub-micron mode indicate effects of sulfur-containing fuel

Box 4.12 Mexico City, Mexico Case Study

Study Source/Reference:
Johnson KS et al., Atmospheric Chemistry and Physics, Vol.6 (2006) 4591-4600.

Funding Source:

Measurement Timeframe:
Samples of $PM_{2.5}$ were collected during the MCMA-2003[50] field campaign from 3 April to 4 May.

Site Characterization:
Centro Nacional de Investigación y Capacitación Ambiental (CENICA), located in a commercial-residential area in southeastern MCMA.

Sampling Equipment: Stacked Filter Units–3-Stage IMPROVE DRUM impactor (UC Davis, CA) in size ranges 1.15–2.5 µm (Stage A), 0.34–1.15 µm (Stage B), and 0.07–0.34 µm (Stage C).

Filter Types: Teflon Strips.

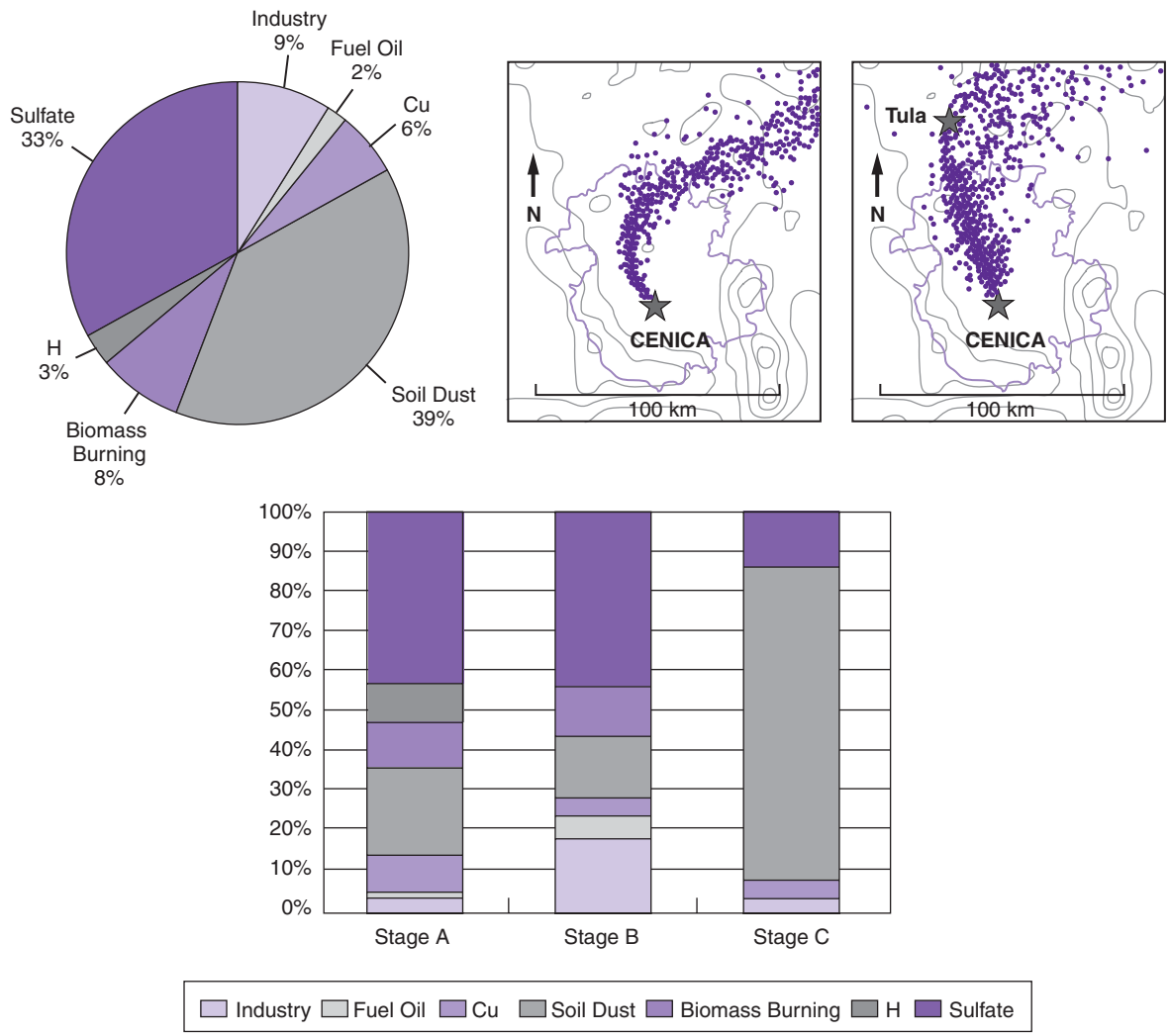
Chemical Analysis: PIXE, Proton-Elastic Scattering Analysis (PESA) and Scanning Transmission Ion Microscopy (STIM).

Receptor Model: PMF.

Source: Johnson et al., (2006).

[10] Mexico City Metropolitan Area (MCMA)-2003 field campaign—http://mce2.org/fc03/fc03.html.

Figure 4.12 Source Apportionment Results for Mexico City, Mexico



Source: Johnson et al., (2006).

Note: In the paper, Johnson et al., presented source contributions for each stage. Pie diagram represents results from the three stages combined and averaged for uniformity with other studies. Back trajectories are for April 9th and 10th, 2003, respectively indicating long range transport of pollutants.

and mobile emissions on sulfate formation in the MCMA, which are not studied. Soil dust is the other dominant source, soil composition during this period was similar to that of paved/unpaved roads based on fugitive dust emissions estimates. Biomass burning which accounted for 43% of the emissions in 1998 (see Figure 2.2) accounts for ~10 percent of the fine PM.

Santiago (Chile)

Results and Recommendations

Results suggest the relevant aerosol sources in Santiago are: resuspended soil dust, vehicular emissions, industrial emissions, copper processing plants, and secondary sulfate aerosols. Copper smelters in the region

Box 4.13 Santiago, Chile Case Study

Study Source/Reference:[51]
University of Sao Paulo (USP), Brazil.

Funding Source:

Measurement Timeframe:
Aerosol sampling was performed during wintertime 2000, with a 12-hour sampling time from July 4 to August 31, 2000.

Site Characterization:
Las Condes sampling station is located in the eastern part of the city, close to the Andes, about 300 meters.

Sampling Equipment: Stacked Filter Units.

Filter Types: 47 mm Nuclepore polycarbonate filters, in two separated size fractions.

Chemical Analysis: PIXE, TEOM®

Receptor Model: Absolute Principal Factor Analysis (APFA).

Measured Concentrations: For winter period, average PM_{10} was 77 µg/m^3 with highs ranging between 20 µg/m^{3}and 160 µg/m^3; For the summer period average PM_{10} was 32 µg/m^3 with highs ranging between 20 µg/m^3 and 80 µg/m^3. The average $PM_{2.5}$ during wintertime was 30 µg/m^3 and 15 µg/m^3 during summertime.

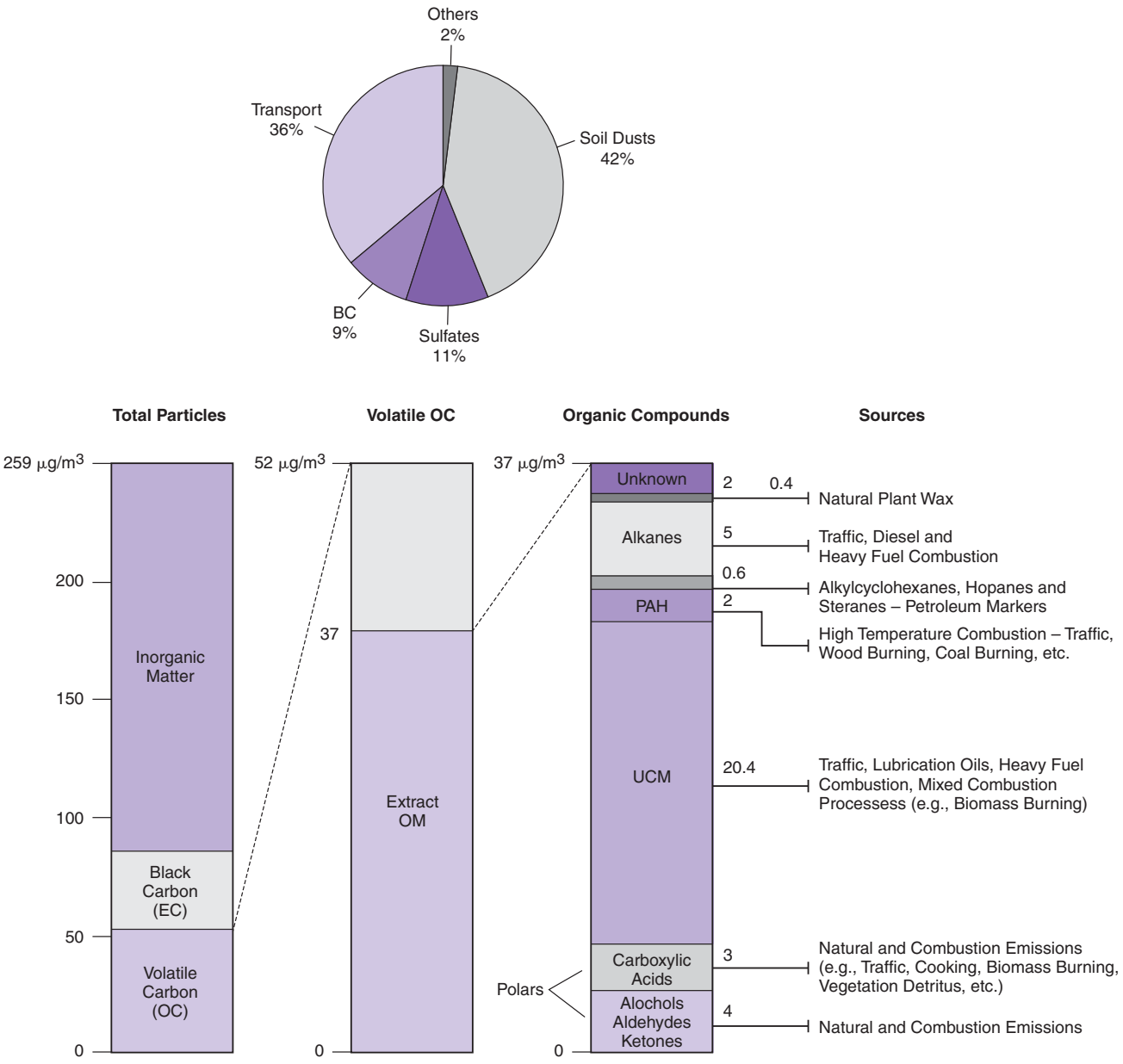
Source: Dr. Paulo Artaxo, University of Sao Paulo, Brazil. Email: artaxo@if.usp.br.

accounted for an average of 10 percent of the fine particulates measured. During winter, the ventilation in the city is poor, with wind speeds of 2 m/s in the evening, and about 1 to 1.5 m/s at night. Due to the low ventilation, PM_{10} averages near 300 µg/m^3 are frequent. The dry weather conditions and frequent inversion layers during wintertime together with the heavy traffic that generates turbulence, makes road dust the most important aerosol source. There is a large inter-relationship between several air pollution sources, due to the common variability caused by the meteorological conditions.

Clearly, transportation, with 900,000 motor vehicles in the city, is the dominant source contribution to the ambient levels. Sulfate particles are also an important component, mainly originating from gas-to-particle conversion from SO_2 from the smelters. Didyk et al., 2000, conducted organic molecular analysis (see Figure 4.14 above) showing a relatively high proportion of uncombusted diesel range hydrocarbons and lubricating oil compounds stressing the contribution of the diesel powered transport sector dominated by an aging bus fleet.

[51] Contact Information: Prof. Paulo Artaxo, University of Sao Paulo, Brazil. Email: artaxo@if.usp.br.

Figure 4.13 Source Apportionment Results for Santiago, Chile



Source: Didyk et al., (2000).

5 Application in Hyderabad, India[52]

Background

Hyderabad is the fifth largest city in India, with a population of approximately 7 million. Due to its prominence as a major high-tech center, it is one of the fastest growing cities, with a population density of ~17,000 persons/square kilometer. In order to improve air quality and develop the local capacity to address this problem, the Andhra Pradesh Pollution Control Board (APPCB), US National Renewable Energy Laboratory (NREL), US Environmental Protection Agency (USEPA), and the World Bank (WB) funded the Hyderabad Source Apportionment Training and Demonstration Project.[53]

One reason to highlight this case is that it provides an example of the importance of linking top-down and bottom-up analyses in the manner needed to develop an effective air quality management system. A thorough and transparent bottom-up emission inventory of stationary and transportation combustion sources was compiled in the first phase of the USEPA Integrated Environmental Strategies (IES) analysis in Hyderabad. The emission inventory included both ambient air pollutants and greenhouse gases (PM_{10}, CO_2, CH_4, and N_2O) for all combustion sources operating within the Hyderabad Urban Development Area for the calendar year 2001. The results of the emission inventory and subsequent air quality modeling indicated that the primary source of PM_{10} emissions in Hyderabad is the transportation sector (~62 percent) with the industrial sector being the second largest source of PM_{10}.

Validation and improvement of the existing emission inventory can further assist environmental managers to identify the major source types contributing to ambient air pollution in a local area through a unique and identifiable emissions signature. Identification of sources and their relative contribution to the total air pollution load can be used to further assist policymakers and modelers in developing integrated control strategies that achieve co-benefits of reducing both particulate matter and greenhouse gases simultaneously.

This project is intended to introduce, demonstrate, and apply the source apportionment techniques presented in this report, in order to assist with air quality management in Hyderabad and provide a unique opportunity to evaluate the initial IES inventory results. In doing so, this project will generate more detailed information on the chemical composition of ambient particulate matter, will further strengthen the technical support for policy makers to make informed environmental management decisions, and improve air quality management in Hyderabad. Specific objectives of this study included:

- Conduct a source apportionment study in Hyderabad.
- Determine the major sources contributing to elevated levels of PM_{10} and $PM_{2.5}$

[52] **Study Team:** Dr. K. V. Ramani (APPCB, India), Dr. Sarath Guttikunda (formerly with WB, U.S.A.), Dr. Alan Gertler (DRI, U.S.A.), Dr. Collin Green (formerly with NREL, USA, currently with USAID), and Ms. Katherine Sibold (EPA, U.S.A.).

[53] Material used during the training, demonstration, and application of source apportionment techniques is based on the material collected from the case studies presented in Chapter 4 and various organizations involved in this exercise.

- Improve and validate the existing emission inventory.
- Train and build capacity in source apportionment analysis and application.
- Strengthen local environmental management and decision making capacity.
- Support industrial and transportation measures that integrate cleaner energy technologies with environmental management techniques.
- Provide data to support integrated policies to reduce both PM and greenhouse gas emissions.

Training workshop material is presented in Annex 8.

Sampling Sites and Methodology

Three sampling sites (see Figure 5.1) listed below were selected from this program.

- *Punjagutta (PUN):* An urban residential/commercial/transport site to the northwest of Hussain Sagar Lake. This location is also a major transit point in the center of the city.
- *Chikkadpally (CHI):* An urban residential/commercial site with significant traffic, which is located southeast of Hussain Sagar Lake. The road is lined on either side with shops and commercial enterprises, small scale industries using coal and oil, and constant traffic because of proximity to twenty cinemas.
- *Hyderabad Central University (HCU):* An upwind sampling location, 20 km from the city center and on the old Hyderabad-Mumbai highway. It stretches over 2300 acres of land, with a sprawling, scenic and serene campus. This site is selected as a background concentration site.

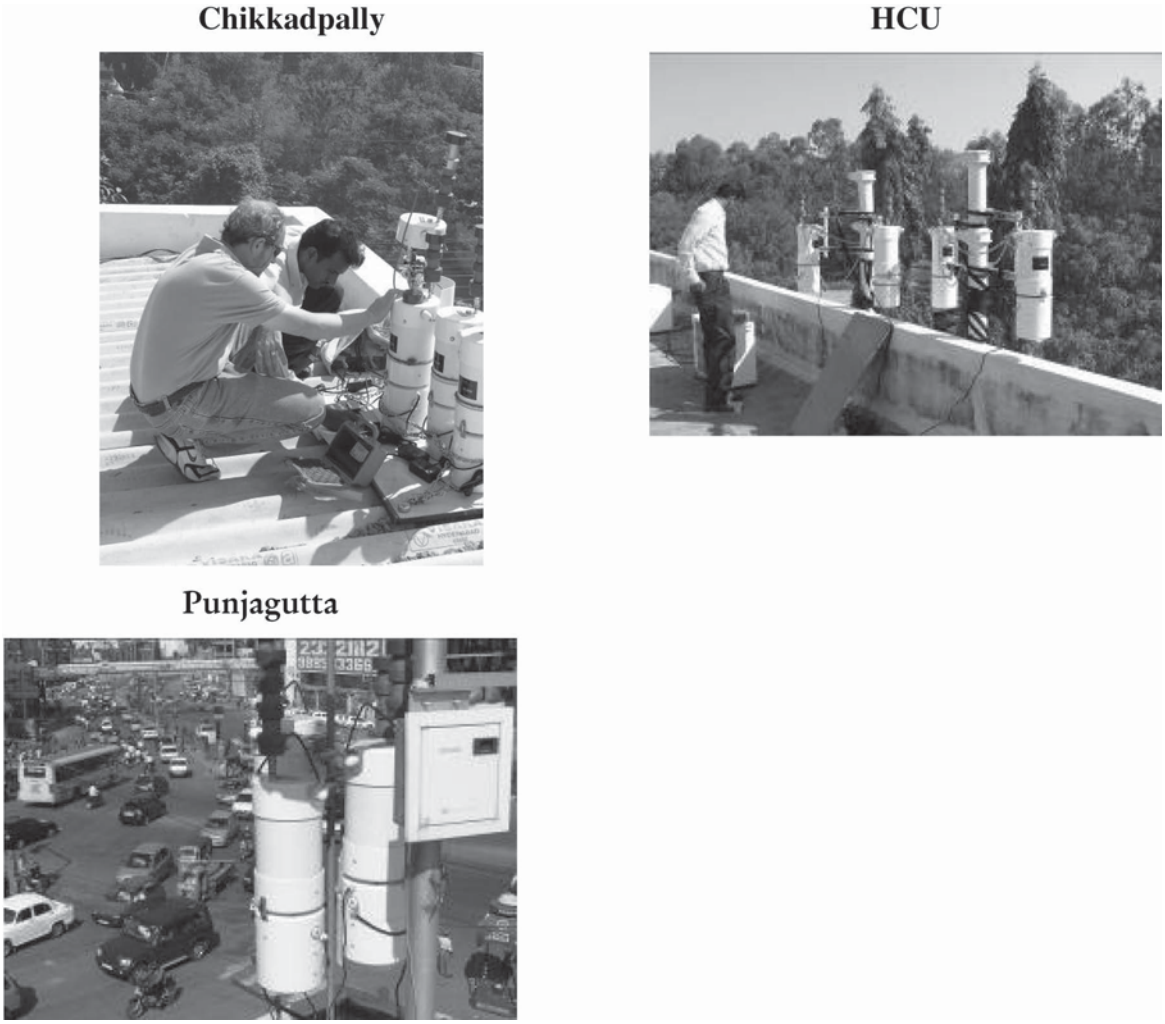
Aerosol samples were collected using twelve Airmetrics MiniVol™ portable air samplers (see Figure 3.2) operating at 5 liters per minute for 24 hour sampling periods. Pairs of Teflon/quartz fiber filters were used to collect aerosol samples every three days. The sampling was conducted in three phases over a period of one year for one month each. Phase 1 (November 12th to December 1st 2005) was characterized as winter season, Phase 2 (May 9th to June 9th 2006) as summer season, and Phase 3 (October 27th to November 18th 2006).

Following sample collection, filters were analyzed. Teflon filters were analyzed for gravimetric mass and metals using x-ray fluorescence. Quartz filters were analyzed for ions using ion chromatography and automated colorimetry, organic and elemental carbon using thermal/optical reflectance, and soluble potassium using atomic absorption spectrometry.

The Chemical Mass Balance (CMB) model version 8.2 (Coulter 2004) was applied to the results for chemical composition from all of the filters, using also chemical source profiles assembled from the DRI source profile data base. The relative source contributions calculated by CMB were compared, both spatially and temporally. Summaries of the results are presented in the next section.[54] Source profiles, which should be representative of the study area during the period when the ambient data were collected, do not exist for Hyderabad and this program did not cover source sampling. From previous environmental studies in Hyderabad (EPTRI 2005), profiles of source types that could impact at the three measured sites were selected and profiles from studies at Georgia Tech, U.S.A. (see India case study in Chapter 4) were utilized. The source composition profiles were tested on a subset of samples from each site, and the optimum set of source profiles and fitting species were selected. Source apportionment analysis was applied to every valid ambient sample, and uncertainties in the source contribution estimated.

[54] For more details on the program please contact Dr. K. V. Ramani, Joint Chief Environmental Scientist, Andhra Pradesh Pollution Control Board, Hyderabad, India. Email: jces@pcb.ap.gov.in. A copy of the final report can be downloaded from www.epa.gov/ies

Figure 5.1 Sampling Sites in Hyderabad, India



Source: Dr. Sarath Guttikunda.

Table 5.1 Measured Mass Concentrations of PM_{10} and $PM_{2.5}$ During the Sampling Period

		PM_{10} (μg/m³)			$PM_{2.5}$ (μg/m³)		
S.No	Station Name	Maximum	Minimum	Average	Maximum	Minimum	Average
Phase 1	Punjagutta	188	127	**160**	99	69	**86**
	Chikkadpally	163	110	**134**	84	57	**69**
	HCU	123	94	**106**	71	46	**56**
Phase 2	Punjagutta	218	28	**111**	87	13	**47**
	Chikkadpally	261	45	**113**	111	16	**43**
	HCU	105	14	**64**	75	6	**26**
Phase 3	Punjagutta	193	56	**122**	136	36	**66**
	Chikkadpally	130	34	**86**	121	23	**54**
	HCU	100	23	**59**	61	15	**40**

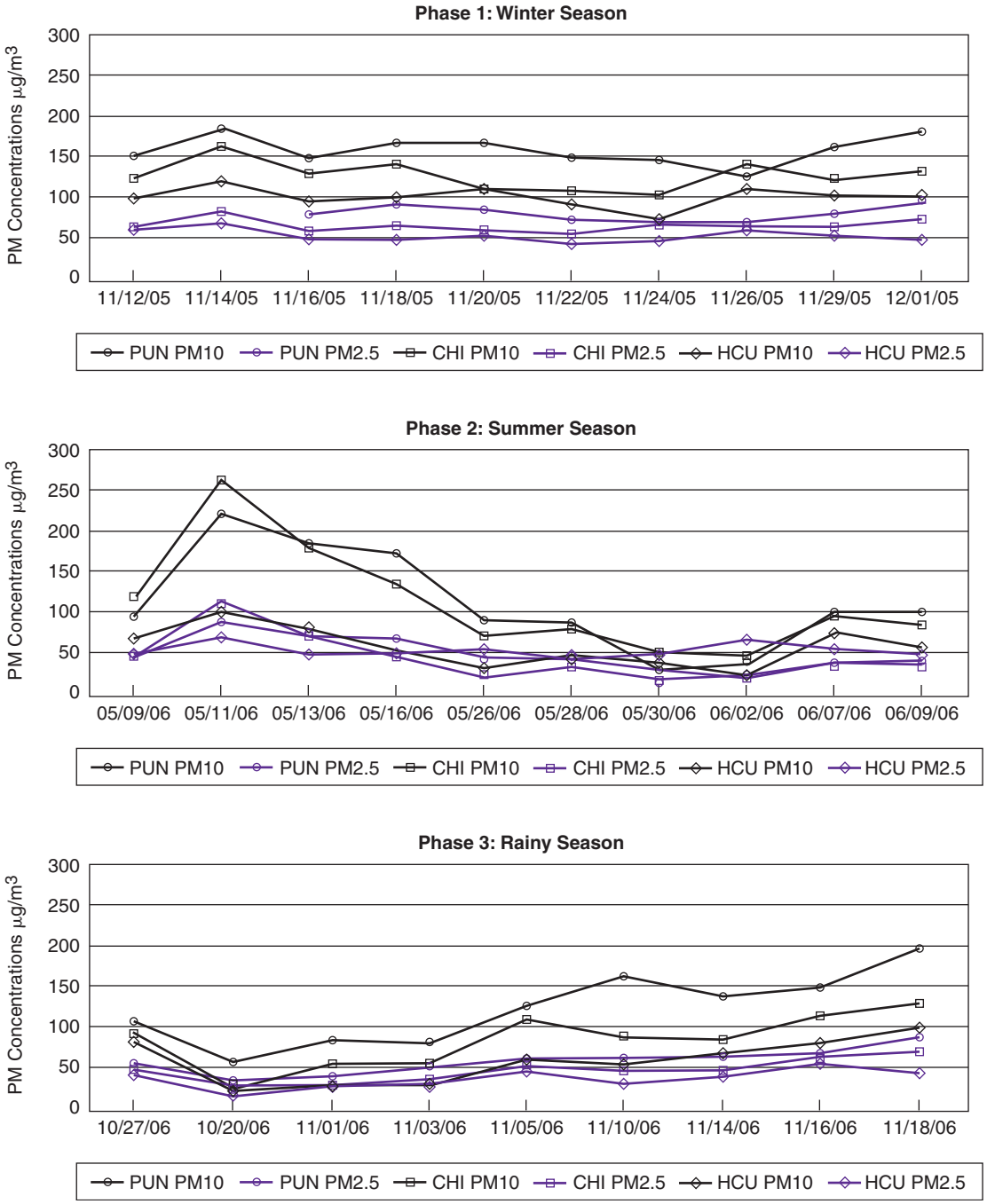
Source: Integrated Environmental Strategies Program (2007).

Results and Conclusions

A summary of the gravimetric results from the three phases is presented in Table 5.1 and times series of samples collected in Figure 5.2.

Punjagutta measured highest average PM_{10} (160 µg/m^3) as well as $PM_{2.5}$ (86 µg/m^3) gravimetric levels during the Phase 1, exceeding the PM_{10} standard (150 µg/m^3) on six of the ten measured days. In the absence of national

Figure 5.2 Measured Mass Concentrations During the Study Months in Hyderabad



Source: Integrated Environmental Strategies Program (2007).

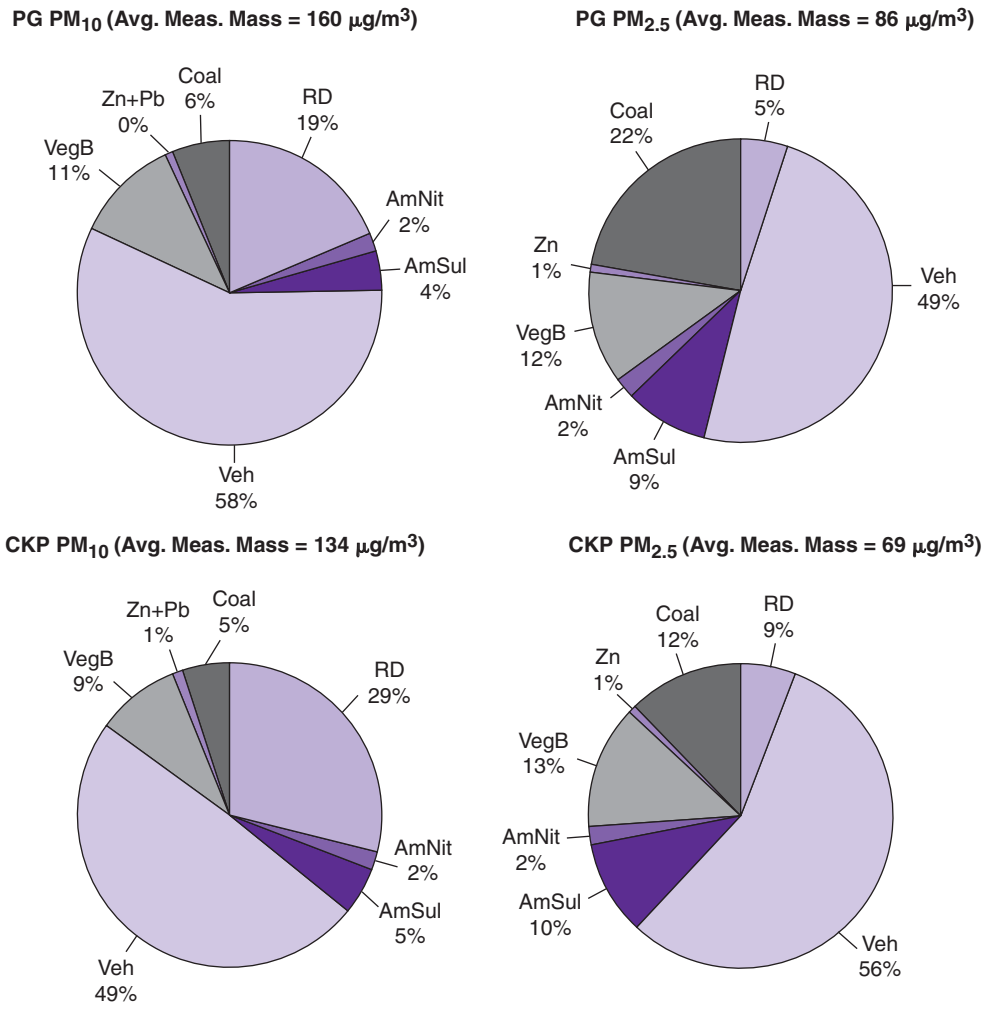
standards for $PM_{2.5}$ the data are compared with USEPA standards of 60µg/m^3 was exceeded on all ten sampling days. Chikkadpally was slightly less polluted with one exceedance for PM_{10} and nine for $PM_{2.5}$ over the ten day period. HCU was substantially cleaner with PM_{10} and $PM_{2.5}$ concentrations approximately 30 percent lower than measured at the two city center sites.

Source attribution results of the CMB modeled ambient samples from the three sites are presented in Figure 5.3 to 5.5. In the absence of local source profiles from Hyderabad specifically or India generally, profiles from other parts of the world were selected for this modeling exercise. Although several profiles from each source type were modeled, only those that provided reasonable statistics for all three sites and both size fractions were retained.

The source profiles selected represent known major source types contributing to the Hyderabad aerosol, i.e. an unpaved dirt road (soil) profile, a mobile source profile (petrol, CNG, and diesel mixed), and a coal combustion profile. Similar source profiles were selected that best modeled both PM_{10} and $PM_{2.5}$ ambient samples from all three sites at Punjagutta, Chikkadpally and HCU, for the month long sampling periods.

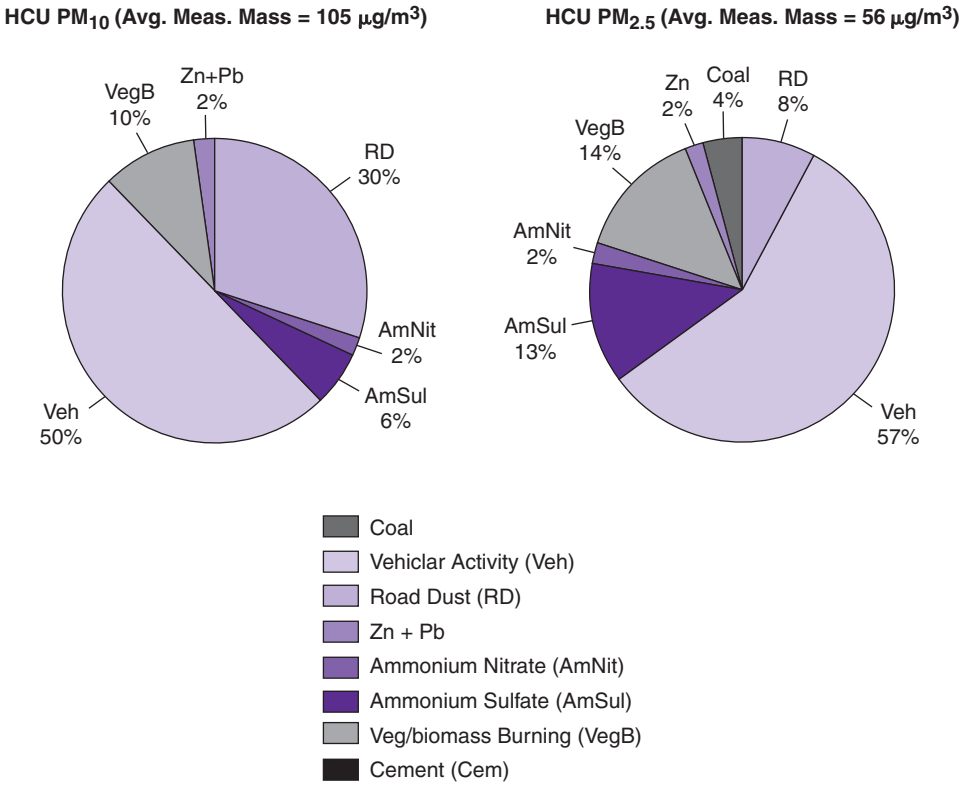
The most important source measured throughout the sampling campaign was mobile

Figure 5.3 Phase 1 (Winter) Source Apportionment Results for Hyderabad, India



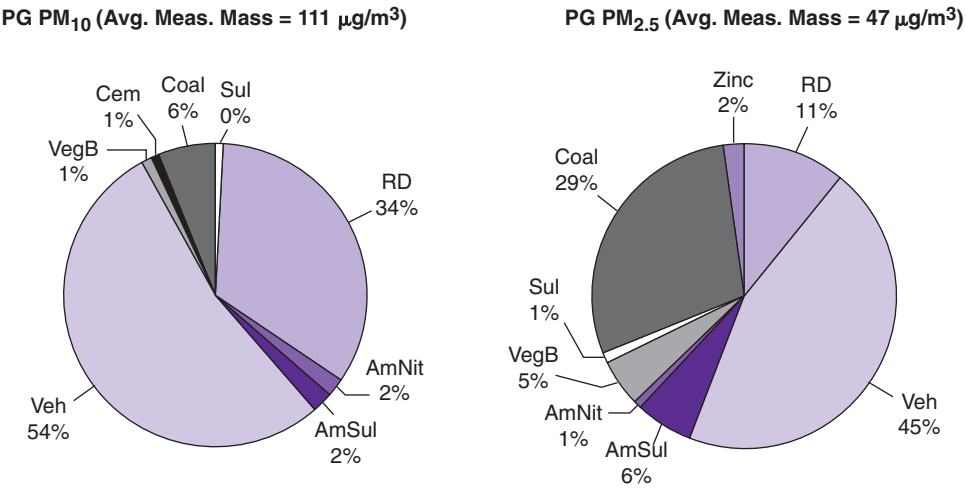
(continued)

Figure 5.3 *continued*



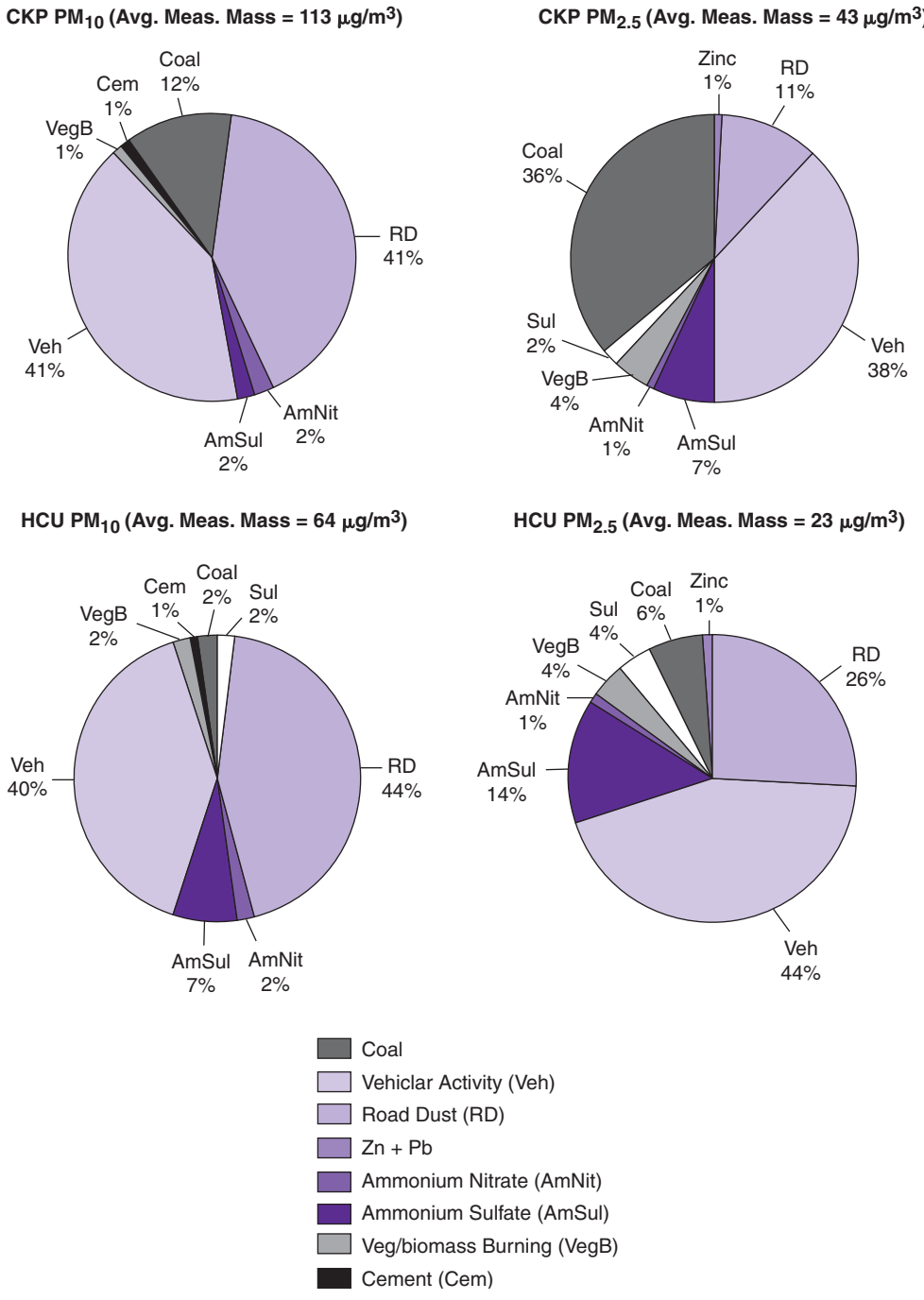
Source: Integrated Environmental Strategies Program (2007).

Figure 5.4 Phase 2 (Summer) Source Apportionment Results for Hyderabad, India



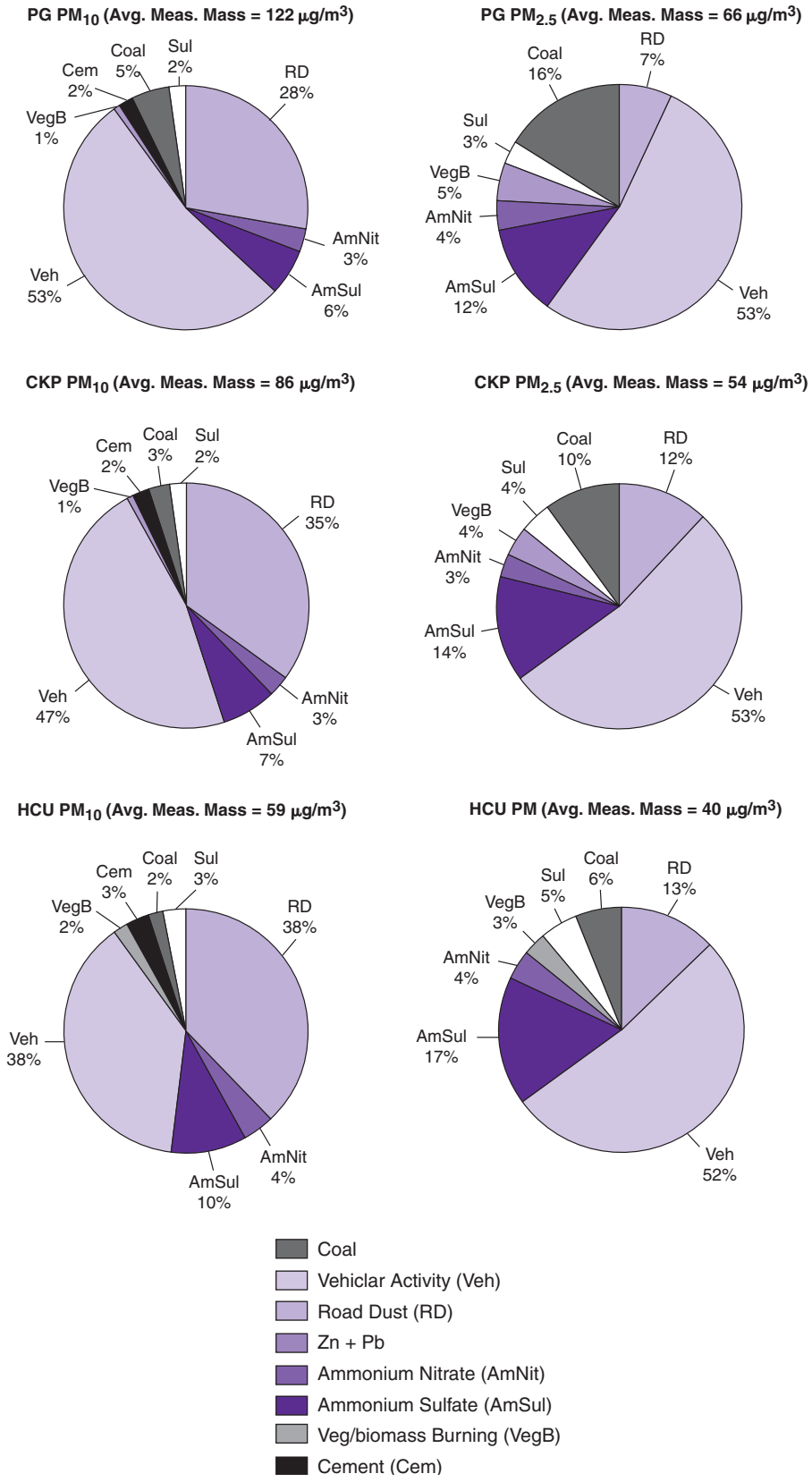
(continued)

Figure 5.4 *continued*



Source: Integrated Environmental Strategies Program (2007).

Figure 5.5 Phase 3 (Rainy) Source Apportionment Results for Hyderabad, India



Source: Integrated Environmental Strategies Program (2007).

sources, varying from 38 to 58 percent for PM_{10}, and 38 to 53 percent for $PM_{2.5}$, for the three sampling sites. As can be expected, the road dust is the second largest source in the PM_{10} size fraction, followed by biomass burning and ammonium. Coal combustion was variable. With large industrial estates in the North and East of the city, and prevalent wind speeds in the direction of the sampling sites, coal contribution was measured as high as 25 percent at Chikkadpally and Punjagutta in the fine fraction.

Major highlights of the receptor modeling are:

- Vehicular activity is the largest contributor to fine and coarse PM fractions, which raises health concerns.
- Construction and traffic activities lead to contributions from re-suspended dust, especially in the fine fraction, which is more harmful to human health at the ground level.
- Waste burning in the residential areas and at landfills is a notable source for fine PM.

Based on this study, results suggest that residents of Hyderabad are exposed to unhealthy levels of PM, with motor vehicles being the major source of the problem.[55] A number of control options were outlined for air pollution control in Hyderabad by Environment Pollution (Prevention & Control) Authority and the pollution control board has identified key areas that have the potential to engineer a fundamental transition to better air quality. These include the following:

- Gaseous fuel programmes, both Compressed Natural Gas and Liquid Propane Gas to leapfrog from current polluting diesel to cleaner fuel, particularly in grossly polluting segments like public buses and auto-rickshaws.
- Public transport and transport demand management to reduce the demand for growth of private motorization and reduce emissions.
- A vehicle inspection program for existing on-road vehicles.
- Management of transit traffic and phasing out of old vehicles to reduce the burden of pollutants in the city.
- Relocation of industries near the center of the city is under consideration along with possible energy efficiency measures.
- Programs for improved solid waste management in the residential sector, including provisions for improved waste collection and landfill management.

[55] Conclusions are entirely those of the team members and should not be attributed in any manner to their affiliated organizations.

6 Implications and Recommendations

This review focuses on receptor-based source apportionment methods. These methods use chemical analysis of relatively few ambient measurements and simple receptor modeling methods to quantify the relative contributions of different sources to ambient PM pollution. Because of the ability to characterize the PM pollution problem, and to quantify the source contributions of PM pollution, these top-down methods can be particularly useful in the context of developing nations, where rather little may be known about the sources of PM. Top-down methods also provide knowledge that will be useful for local air quality managers and scientists as they attempt to achieve the longer-term goal of bottom-up modeling of PM.

Lessons from the Case Studies

The results of numerous case studies where PM source apportionment methods were successfully applied in developing countries are presented in this report. In all of these cases, useful knowledge was gained as to the relative contributions of different sources to ambient PM levels. Such knowledge is critical in formulating effective air quality management systems.

The case studies illustrate a wide variety of tools and techniques available to conduct source apportionment. These methods range from simple pollution plots to complex meteorological trajectory models; multivariate and mass balance receptor models; optical microscopy; and combinations thereof.

When conducting a study similar to the ones discussed in this report a clear understanding of the goals of the analysis (i.e., a precise statement of the questions to be answered by the investigation), familiarity with the range of possible analysis techniques and their individual advantages and limitations is required. Table 6.1 presents a series of decisions to be made by urban area officials or an institution planning to conduct a source apportionment study.

Critical inputs needed when conducting effective bottom-up and top-down analyses are quality emission inventories and source profiles, respectively. Unfortunately, these are lacking for many developing country cities. However, bottom-up and top-down analyses are not all or nothing activities. That is, **effective air quality management systems can be viewed as a process of growth from relatively weak systems utilizing relatively primitive analytical techniques and data to highly effective systems utilizing sophisticated techniques.** This is the case for three reasons. First, in the absence of a developed management system, useful information can be generated from first level, back-of-the-envelope, inexpensive analysis. With this type of analysis, development of emission inventories and source profiles can rely on information from regions with similar characteristics. That is, an area can begin their air quality management system with off-the-shelf inputs and local ambient measurements. From this base, an iterative process of repeated model improvement can be utilized to develop more sophisticated emission inventories and source profiles which include region-specific information. The iterative process of improving the models is based on analyzing the inconsistencies that result from each round of bottom-up and top-down analyses. This

Table 6.1 Decisions for Implementing a Successful Top-down Source Apportionment Study

Steps	Description
Background	Specific information on trends in pollution, types of sources, potential hot spots, physical characteristics of the city, criteria pollutants of interest, and local capacity to conduct source apportionment.
Site Location	Numbers of sites and decisions on locations with good representativeness of city sources and pollutant mix.
Sampling Frequency	Frequency of sampling is partly determined by the study objectives. For example, continuous samplers used for compliance will be operating every day, while others may operate only on a seasonal basis. This decision also depends on the type of sampler available.
Samplers	Type of sampler and filter media is based on the availability of compatible chemical analysis techniques.
Chemical Analysis	Availability of instruments and capacity to operate. Often the academic institutions in the region have the capacity to undertake such analytical tasks, but if not, this task can be outsourced.
Receptor Modeling	Selection of a receptor model. (This will also influence the type of chemical analysis required for data).
Emission Inventory	While emission inventories are not directly utilized in a top-down analysis, they are useful in estimation of source strengths and identification of source profiles to help ensure efficient and effective receptor modeling. For example, having an emission inventory can assist in determining where to locate receptors including determining the location of possible hot spots.
Source Profiles	Locally specific source profiles are desired, but availability of profiles from representative regions may be acceptable.
Decision Making	Based on the apportionment results, review of possible technical, institutional, economic, and policy measures.

Source: Authors' calculations.

eventually leads to a high quality evaluation system where the top-down and bottom-up analyses approach convergence.[56] However, the process cannot stop here. Measurements should continue and models need to change as the pollution characteristics of the region being managed changes. That is, **the management system needs to reflect the changing economic activity of the urban area being managed.** Finally, as improved evaluation technology and analytical techniques become available the system needs to be updated to reflect the improvements.

The technical capacity to conduct both top-down and bottom-up studies in developing countries is still an issue. For the majority of the top-down analyses listed in this report, a collaborative effort was undertaken with the analysis being conducted outside of the region. On one hand, collaborations like these help develop local capacity, since a local institution is always involved in the process of sample collection, filter management, and final estimation of sources. On the other hand, the capability to conduct a full scale study in the receptor region is desirable. One of the main

[56] While the top-down and bottom-up results are expected to begin converging, it is unlikely they will fully converge because of the complicated nature of air pollution analysis.

barriers is the chemical analysis stage, where access to and operational training on equipment such as XRF, IC, etc., are oftentimes lacking. Fortunately, the tools and techniques needed to conduct these studies are becoming more widely available, which facilitates developing countries acquiring the technical capacity to conduct all aspects of source apportionment studies. The extensive bibliography in Annex 7 is intended to provide a comprehensive list of institutions and individuals available locally or regionally that have expertise in conducting these type studies. They may be able to serve as invaluable resources as top-down and bottom-up studies are undertaken.

There is an acute need for source apportionment analysis in developing countries, and with proper training and capacity development (both technical and financial) source apportionment can make a valuable contribution in attempts to reduce air pollution. Utilization of source apportionment techniques is expanding, especially in Africa and Asia, and these techniques are increasingly aiding environmental compliance and answering policy-relevant questions like what sources to target for pollution abatement efforts, where to target (e.g., suspected hot spots), and how to target.

Major Pollution Sources

Because analytical techniques and goals vary, it is difficult to make direct comparisons of pollution sources across urban areas. However, there are enough commonalities in source categories that an indirect comparison can be made. Table 6.2 provides a summary of the equipment, analytical methods and source apportionments from the case studies in Chapter 4. This provides a sense of the equipment and analysis techniques used for a wide variety of source apportionments. Table 6.3 presents a summary of the source contribution results for these case studies. For each urban area listed in Table 6.3, one of the categories is highlighted as representing the largest PM contributor. Also note that some of the categories overlap in their definitions, which points out a lack of uniformity in source apportionment studies. The commonly identified source categories include: coal burning and associated secondary pollutants such as sulfates and nitrates (sometimes over 50 percent of the mass), mobile sources (more than 40 percent of the mass in highly motorized cities), crustal sources (typically the most common crustal sources in urban areas are due to resuspension of road dust and construction activities), biomass burning (including biomass fuels used for cooking in the rural areas), industrial activities, smelters and metal processing, power plants (where they are located within the city limits), and marine sources (such as sea salt) in coastal regions.

The most common source identified in the cases presented in this report is *dust emissions*. Dust sources include: 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, it can often be difficult to quantify such emissions. As presented in Figure 2.2, some urban areas included dust emissions from roads in their emission inventory. However, this is typically a rough estimate because it is difficult to track the number and types of vehicles on roads, conditions of the roads, and entrainment factors for dust which are partly dependant on the local meteorological conditions. Additionally, there are no specific emission factors established that can be applied to all urban areas.

Some control measures for dust include: (i) minimizing track-out onto paved roads; (ii) covering materials in trucks; (iii) rapidly cleaning up material spills on roads; (iv) employing street cleaning/sweeping, (v) washing or otherwise treating the exterior of vehicles—personal and public; (vi) keeping roadway access points free of materials that may be carried onto the roadway; (vii) restricting speed limits; (viii) paving unpaved roads; and (ix) promoting vegetation of dry areas lacking vegetative cover. Implementation of many of these measures requires capacity at the municipal and city level.

In developing countries, urban clusters of ***small-scale manufacturers*, such as**

Table 6.2 Summary of Techniques from Source Apportionment Studies

Shanghai		Beijing		Xi'an	
Samplers Hi-Vol. $PM_{2.5}$ Med-Vol $PM_{2.5}$ **Filters** Quartz for organic Teflon for element **Analysis** ICP-AES & XRF **Receptor Model** CMB	**Measured** Road dust Other dust Transport Industry Power plant Marine	**Samplers** Collocated dichotomous **Filters** 37 mm dia. cellulose ester & quartz Teflon **Analysis** IC, XRF NIOSH thermal Optical, GC/MS **Receptor Model** CMB and PMF	**Measured** Road dust Transport Industry Coal burning Biomass & open burning Secondary aerosols Other	**Sampler** Mini-Vol™ **Filter** Pre-fired quartz-fiber **Analysis** TOR for OC & EC Using IMPROVE protocol **Receptor Model** APCA	**Measured** Diesel transport Gasoline transport Coal burning Biomass & open burning
Delhi, Kolkata, Mumbai, Chandigarh		**Dhaka, Rajshahi**		**Cairo**	
Sampler Caltech $PM_{2.5}$ filter sampler **Filter** Quartz fiber; pre-washed nylon PTFE **Analysis** XRF, IC, GC/MS, Carbon Analyzer, Gravimetric **Receptor Model** CMB	**Measured** Road dust Diesel transport Gasoline transport Coal burning Biomass & open burning Secondary aerosols Other	**Sampler** GENT stacked filter **Filter** Neuclepore polycarbonate **Analysis** PIXE **Receptor Model** PMF	**Measured** Road dust Other dust Transport Gasoline transport Industry Marine Other	**Sampler** MiniVol™ **Filter** Teflon-membrane quartz-fiber **Analysis** XRF, IC and TOR **Receptor Model** CMB	**Measured** Other dust Transport Industry Biomass & open burning Marine Secondary aerosols
Qalabotjha		**Bangkok**		**Hanoi**	
Sampler MiniVol™ **Filter** Teflon membrane & Quartz fiber **Analysis** XRF, IC and TOR **Receptor Model** CMB	**Measured** Other dust Industry Biomass & open burning Secondary aerosols Other	**Sampler** Collocated dichotomous **Filter** 37 mm dia. cellulose ester & quartz, Teflon in wet season **Analysis** XRF, IC Gravimetric, Reflectometer NIOSH method **Receptor Model** CMB	**Measured** Other dust Transport Industry Biomass & open burning Marine Secondary aerosols	**Sampler** Gent Stacked Filter **Filter** 47 mm dia. Nuclepore polycarbonate **Analysis** IC for water soluble ions Reflectance method for BC **Receptor Model** PMF and PSCF	**Measured** Other dust Transport Coal burning Long-range transport Marine Secondary aerosols

(continued)

Table 6.2 *continued*

Sao Paulo		Mexico City		Santiago	
Sampler Stacked Filter Units **Filter** 47 mm Nuclepore polycarbonate in 2 size fractions **Analysis** PIXE, TEOM® **Receptor Model** APFA	**Measured** Road dust Transport Industry Secondary aerosols	**Sampler** Stacked Filter IMPROVE DRUM impactor **Filter** Teflon strips **Analysis** PIXE, Proton-Elastic Scattering, Scanning Transmission Ion Microscopy **Receptor Model** PMF	**Measured** Other dust Industry Biomass & open burning Secondary aerosols	**Sampler** Stacked Filter Units **Filter** 47 mm Nuclepore polycarbonate in 2 size fractions **Analysis** PIXE, TEOM® **Receptor Model** APFA	**Measured** Other dust Transport Secondary aerosols Other

Source: See Chapter 4 Case Studies for source information.

Table 6.3 Summary of Results from Source Apportionment Studies

				Dust (%)		Transport (%)			Industry (%)			Non-urban (%)			%	%
City	Country	PM Size	Study Period	RD	OD	T	D	G	I	CB	PP	BB	LRT	MA	SA	O
Shanghai	China	PM2.5	Autumn	2		17			29		28			24		
			Winter 2001	2		16			31		24			27		
			Spring 2001	3	1	19			33		23			21		
			Summer 2001	3	2	12			37		15			32		
			Annual	3	1	16			33		22			26		
Beijing	China	PM2.5	Annual 2000	9		8			6	19		11			31	18
Xi'an	China	PM2.5	Fall 2003				23	73				4				
			Winter 2003				3	44		44		9				
Delhi	India	PM2.5	Spring 2001	16			18	4		2		22			16	23
			Summer 2001	41			23	2		1		10			15	9
			Autumn 2001	18			16	3		2		21			10	30
			Winter 2001	4			16	7		9		29			20	15
			Annual	20			18	4		3		20			15	19
Mumbai	India	PM2.5	Spring 2001	38			25	3		0		13			19	2
			Autumn 2001	23			20	2		1		21			17	16
			Winter 2001	16			21	5		4		13			19	22
			Annual	26			22	3		2		16			18	10
Kolkata	India	PM2.5	Spring 2001	28			24	11		4		19			20	
			Summer 2001	21			61	8		1		24			14	
			Autumn 2001	7			43	21		5		32			11	
			Winter 2001	5			15	9		13		17			10	30
			Annual	15			36	12		6		23			14	8
Chandigarh	India	PM2.5	Summer 2001	32			7	17				9			24	10

(continued)

Table 6.3 *continued*

				Dust (%)		Transport (%)			Industry (%)			Non-urban (%)			%	%
City	Country	PM Size	Study Period	RD	OD	T	D	G	I	CB	PP	BB	LRT	MA	SA	O
Dhaka	Bangladesh	PM2.5	2001-02 Univ	19	10	39		9	22					1		
			2001-02 Farmgate		1	43		2	41							13
		PM10	2001-02 Univ	7	44	40		4	1					4		
			2001-02 Farmgate		53	23		13	2					9		
Rajshahi	Bangladesh	PM2.5	2001-02	5	2	29			50					14		
		PM10	2001-02	14	50	23								13		
Cairo	Egypt	PM2.5	Fall 1999		6	16			9			46			23	
			Winter 1999		11	18			27			17		1	26	
			Summer 2002		8	31			12			29		2	18	
		PM10	Fall 1999		31	8			8			39		2	12	
			Winter 1999		29	12			19			22		3	14	
			Summer 2002		44	12			8			24		3	9	
Qalabotjha	S. Africa	PM2.5	1997		62				1			14			9	14
		PM10	1997		54				2			20			8	16
Bangkok	Thailand	PM2.5	Dry 2002-03		5	35			2			26			32	
			Wet 2002-03		12	33			3			33			19	
		PM10	Dry 2002-03		60	11						17		2	9	
			Wet 2002-03		65	5			2			21		1	6	
Hanoi	Vietnam	PM2.5	1999-01		4	5				28			45	8	10	
		PM10	1999-01		32	7				26			2	22	11	
Bandung	Indonesia	PM2.5	Dry 2002-03		25	15			25				15			20
			Wet 2002-03		21	20			22				16			20
		PM10	Dry 2002-03		21	20			21				17			20
			Wet 2002-03		22	20			22				14			21
Sao Paulo	Brazil	PM2.5	Winter 1997	25		28			23						23	
			Summer 1998	30		24			27						17	
Mexico City	Mexico	PM2.5	2003		39				20			8			33	
Santiago	Chile	PM2.5	2000		42	36									11	2

RD = Road Dust; OD = Other Dust (Soil Dust, Resuspension; Fugitive Dust, Construction); T = Transport; D = Diesel; G = Gasoline; CB = Coal Burning; BB = Biomass & Open Burning; PP = Power Plants; I = Industry & Commercial including Oil Burning & Brick Kilns; LRT = Long Range Transport; MA = Marine; SA = Secondary Aerosols; O = Others

Source: See Chapter 4 for Case Studies for source information.

leather tanneries, brick kilns, smelters, and metalworking shops, can create severe environmental problems. In some of the case studies, where source profiles were available, these were identified as a major source—some are seasonal like the brick kilns in Dhaka and Rajshahi, Bangladesh, and some yearlong like copper smelters in Mexico City. Such polluters are difficult for regulators to identify, much less monitor. However, innovative environmental management strategies can be effective. For example, relocation has proven very successful in the case of reducing Delhi air pollution. Another particularly promising approach is to introduce clean technologies that prevent pollution without unduly raising production costs.

While not the highest PM contributor in any of the Chapter 4 cases, ***coal-fired power plants* can be important contributors to ambient PM and regional haze, mostly by conversion of their SO_2 emissions to sulfates during transport.** In countries like China, the acid rain and sulfur pollution from coal fired power plants is a major concern (ESMAP 2003).

In addition to power plants, *large- and small-scale industries* are also likely major contributors to local pollution levels. Large-scale sources with tall stacks contribute most to the long-range transport; small-scale sources may have even greater emissions, but they contribute mostly to local ambient concentrations in densely populated areas. Given the economies of scale—both technically and institutionally—regulatory regimes for large emission sources, such as power plants and key specialty industries, can greatly reduce total emissions, long-range transport, and impacts, depending on how close they are to major urban areas.

In the rural areas and in secondary cities, ***biomass burning* is one of the major sources of pollution which is poorly characterized and is believed to contribute anywhere from 10–60 percent of the ambient PM levels, depending on where it is being measured.** For regions like Africa, the main pollution source is the residential sector where a combination of coal and biomass (wood, field residue, and dung) are most commonly used. The scarcity of firewood often leads to substitutes which have higher emission levels than wood, for example crop residues and dung. Although a transition to electricity, gas, or renewables would be the healthiest solution, the complete transition from biomass fuels in the poorer urban and rural communities will take time, owing to costs and supply.

The *transportation sector* along with the resulting indirect emissions—fugitive dust or resuspension—is one of the major sources of fine and coarse PM pollution in megacities and up-and-coming urban areas. Transportation is also responsible for an increasing portion of the energy consumption and thereby for many of the harmful effects on the environment. Air pollution from transportation can be localized or have trans-boundary and global effects. In dense traffic zones, pollutants are emitted near populations that are potentially exposed whereas other pollutants can travel long distances before they are deposited on the ground. The emission of greenhouse gases (especially CO_2), of which transportation is one of the main sources, have been shown to lead to global impacts on climate. A detailed review of the impacts of urban transport, control measures, and implications are discussed in detail in *Reducing Air Pollution from Urban Transport* (World Bank 2004b).

Field Burning clears fields of plant residue, preparing the soil for planting without the need for tillage. Some farmers believe that burning increases crop yield and helps control weeds and pests. Unfortunately, the small soot particles from field burning and other combustion sources, such as coal-burning power plants, travel across large distances and easily enter buildings. This was one of the major sources identified in Bangkok.

Implications for Policymakers

The major purpose of this report is to describe techniques available for identifying air pollution types and sources. As illustrated in Figure 1.3, these techniques are critical in formulating an effective air quality management system (AQMS). **In particular, top-down, receptor-based source apportionment is a useful tool for developing countries that have not amassed a detailed, accurate information base of pollution sources. By utilizing a first-level analysis with only a few samples, air quality managers can improve their knowledge of potential pollution sources and revise their air quality management strategies to deal more efficiently with air pollution problems.**

That is, the implementation of an effective air quality management system in an urban area it is not an all or nothing proposition, and source apportionment offers a powerful tool in improving an AQMS. For example, **an urban area can set an ultimate air quality goal with interim targets to be met along the way.** In fact, the World Health Organization provides suggested interim targets for meeting their new PM_{10} and $PM_{2.5}$ guidelines. These interim goals allow the governing authority to build their AQMS gradually and gain competency while allowing local polluters time to reduce emissions.

Utilization of top-down techniques can assist in improving the emission inventory, monitoring, control strategies, and air quality modeling portions of the AQMS. It is often observed that early emission inventories may be incomplete and inaccurate. Refinements can be made through building monitoring capacity, continued identification of pollution sources, and utilization of top-down studies. In short, utilizing top-down techniques, in conjunction with bottom-up methods, forms a key element in building and maintaining an effective AQMS.

For the first-level receptor-based studies; source profiles from other urban areas can be used, collection sites can be limited with a modest number of samples from each site, and data analysis can be outsourced. All these measures will reduce the initial costs of the analysis yet provide useful information. Further work will provide increasingly improved information and can be better targeted to address specific issues of concern.

Another significant problem in building an effective AQMS will likely be the availability of trained scientists and technicians to conduct the top-down and bottom-up analyses. As with the data analysis, in the beginning much of the technical responsibilities can be outsourced. One potentially inexpensive way to build capacity locally is funding the necessary graduate studies of qualified local residents. Locally-based top-down and bottom-up analyses can be incorporated into the graduate programs of these students and the AQMS can be advanced during and after the graduate program.

Additionally, because of the expected long-term growth of energy use in developing country cities, **governing authorities may be able to find allies to assist in building an effective AQMS via the source apportionment techniques presented in this report.** An example is partnering with those interested in reducing greenhouse gases. Another example is a policy that reduces automotive air pollution by reducing the reliance on automobiles. The result could produce collateral benefits of reduced congestion on roads and shorter trip times for drivers. Top-down analysis may help build a case for these partnerships.

Effective air quality management includes ensuring thorough and reliable monitoring of ambient concentrations as well as: keeping the authorities and the public informed about the short- and long-term changes in air quality; developing accurate emission inventories; keeping an inventory of sources of various pollutants; analyzing the dispersion of pollutants emitted from various sources; measuring the impacts of pollutant exposure on health; assessing the results of abatement measures; and thereby providing the best abatement strategies possible within the given available resources. Such a management system is especially lacking in secondary urban areas of developing countries. To make the best decisions when developing strategies, analysts and policymakers need to understand the intensity of local emission sources, the sources that impact the local community the most, and the potential effects of a wide range of abatement measures on the different source sectors involved. Top-down source apportionment helps to provide this knowledge.

In developing effective air quality management systems, overcoming knowledge gaps is critical. Fortunately, a wealth of new data on $PM_{2.5}$ and PM_{10} constituents, pollution trends, main sources, and pollution chemistry, is becoming available on a routine basis as the results of new bottom-up and top-down analyses are published. This new information along with a growing commitment to utilizing scientifically-based analytical techniques within the framework of sound air quality management systems offers developing countries the hope of gaining control over the significant air pollution challenges that accompany rapid urban area development.

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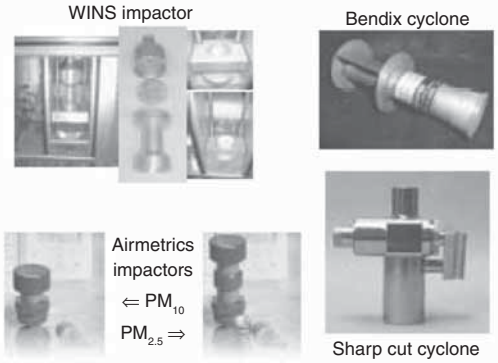
Annex 1 Aerosol Sampling Systems

Figure A1.1 Aerosol Sampling Systems

I. Inlets . . . *Fine Particle Inlets*

Type	Cut Point (d_{50})	Slope $\left(\sqrt{\frac{d_{84}}{d_{16}}}\right)$	Flow Rate
Harvard sharp cut impactor	2.5 µm	1.02	4 L/min
R&P sharp cut cyclone	2.5 µm	1.23	5 L/min
GRT sharp cut cyclone	2.5 µm	1.24	6.8 L/min
Harvard sharp cut impactor	2.5 µm	1.06	10 L/min
URG cyclone	2.5 µm	1.32	10 L/min
EPA WINS impactor	2.48 µm	1.18	16.7 L/min
BGI sharp cut cyclone	2.5 µm	1.19	16.7 L/min
URG cyclone	2.5 µm	1.35	16.7 L/min
Harvard sharp cut impactor	2.5 µm	1.25	20 L/min
Andersen/AIHL cyclone	2.7 µm	1.16	24 L/min
Improve cyclone	2.3 µm	1.18	28 L/min
Bendix/Sensidyne 240 cyclone	2.5 µm	1.7	113 L/min

I. Inlets . . . *Examples of Inlets*



I. Inlets . . . *PM_{10} Inlets*

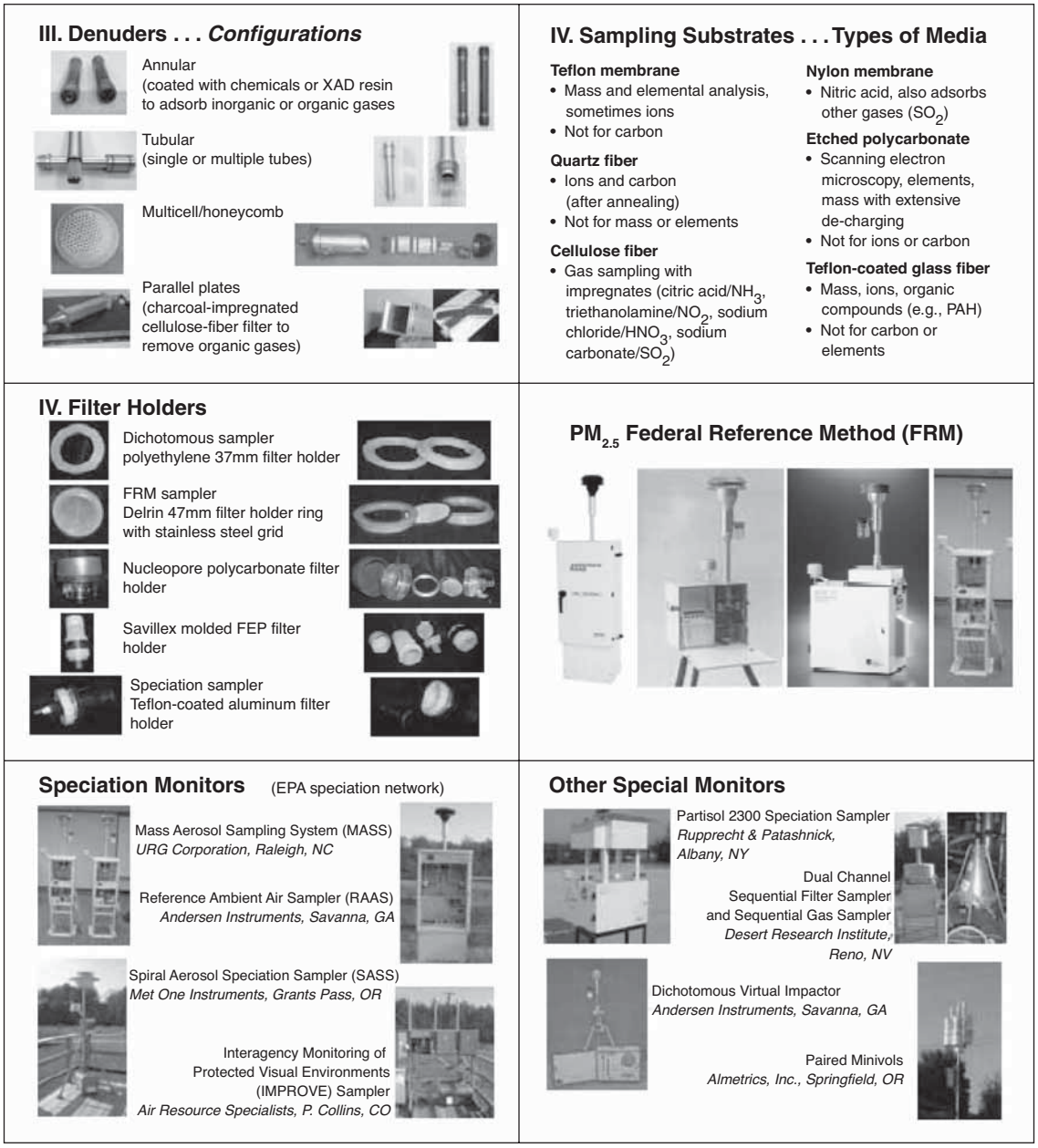
Type	Cut Point (d_{50})	Slope $\left(\sqrt{\frac{d_{84}}{d_{16}}}\right)$	Flow Rate
Harvard sharp cut impactor	10 µm	1.11	4 L/min
Harvard sharp cut impactor	10 µm	1.09	10 L/min
Andersen 246B impactor	10.2 µm	1.41	16.7 L/min
Harvard sharp cut impactor	10 µm	1.06	20 L/min
Andersen med-vol impactor	10 µm	1.6	113 L/min
Andersen hi-vol impactor	9.7 µm	1.4	1,133 L/min
TEI/Wedding cyclone	9.6 µm	1.37	1,133 L/min

I. Inlets . . . *Examples of PM_{10} Inlets*

(continued)

Source: Chow and Watson (2003).

Figure A1.1 *continued*



Source: Chow and Watson (2003).

Annex 2 Characteristics of Commonly Used Filter Media

Table A2.1 Characteristics of Commonly Used Filter Media

Filter Type, (Major Manufacturer)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods
Ringed Teflon-membrane (Gelman Scientific; Ann Arbor, MI)	25 mm 47 mm	Thin membrane stretched between polymethylpentane ring. White surface, nearly transparent. Minimal diffusion of transmitted light. High particle collection efficiencies. Cannot be accurately sectioned. 1.2, 2.0, 3.0, 5.0 and 10 pm pore sizes (determined from liquid filtration). Melts at ~60°C. High flow resistance.	Usually low blank levels, but several contaminated batches have been found. Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Low hygroscopicity. Low blank weight.	Gravimetry, OA, XRF, PIXE; INAA, AAS, ICP/AES, ICP/MS, IC, AC.
Backed Teflon membrane, (Gelman Scientific, Ann Arbor, MI)	47 mm	Thin membrane mounted on thick polypropylene backing. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Melts at ~60°C. High flow resistance.	Usually low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Inert to adsorption of gases. Higher background levels for XRF and PIXE than Teflon owing to greater filter thickness. Low hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC.

(continued)

Table A2.1 *continued*

Filter Type, (Major Manufacturer)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods
Nylon membrane, (Gelman Scientific, Ann Arbor, MI)	25 mm 37 mm 47 mm	Thin membrane of pure nylon. White opaque surface, diffuses transmitted light. 1 μm pore size. Melts at –60°C. High flow resistance.	High HNO_3 collection efficiency. Passively adsorbs low levels of NO, NO_2, PAN, and SO_2. Low hygroscopicity. Low blank weight.	IC, AC
Silver membrane (Millipore Corp., Marlborough, MA)	25 mm 37 mm	Thin membrane of sintering, uniform metallic silver particles. Grayish-white surface diffuses transmitted light. Melts at –350°C. High flow resistance.	Resistant to chemical attack by all fluids. Passively adsorbs organic vapors. Low hygroscopicity. High blank weight.	Gravimetry, XRD.
Cellulose esters membrane (Millipore Corp., Marlborough, MA)	37 mm 47 mm	Thin membrane of cellulose nitrate mixed esters, and cellulose acetate. White opaque surface diffuses transmitted light. 0.025, 0.05, 0.1, 0.22, 0.30, 0.45, 0.65, 0.80, 1.2, 3.0, 5.0, and 8.0 pm pore sizes. Melts at –70°C. High flow resistance.	High hygroscopicity. Negligible ash content. Dissolves in many organic solvents. Low hygroscopicity. Low blank weight.	Gravimetry, OM, TEM, SEM, XRD Biomedical applications.

(continued)

Table A2.1 *continued*

Filter Type, (Major Manufacturer)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods
Polycarbonate membrane, (Corning Costar, Cambridge, MA)	47 mm[b]	Smooth, thin, polycarbonate surface with straight through capillary holes Used for particle size classification. Light gray surface, nearly transparent. Minimal diffusion of Transmitted light. Low particle collection efficiencies, < 70% for some larger pore sizes. Retains static charge. 0.1, 0.3, 0.4, 0.6, 1.0, 2.0, 3.0, 5.0, 8.0, 10.0, and 12.0 gm uniform pore sizes. Melts at –60°C. Moderate flow resistance.	Low blank levels (made of carbon-based material, so inappropriate *for* carbon analysis). Low hygroscopicity. Low blank weight.	Gravimetry, OA, OM, SEM, XRF, PIXE.
Polyvinyl Chloride membrane (Millipore Corp., Marlborough; MA).	47 mm	Thin membrane of cellulose nitrate. White opaque surface, diffuses transmitted light. 0.2, 0.6, 0.8,2,0, and 5.0 μm pore sizes. Melts at –50°C. High flow resistance.	Dissolves in some organic solvents. High hygroscopicity. Low blank weight.	XRD
Pure quartz-fiber (Pallflex Corp., Putnam, CT)	25 mm 37 mm 47 mm 20.3 × 25.4 cm	Mat of pure quartz fibers. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Soft and friable edges flake in most filter holders. Melts at > 900°C. Moderate flow resistance.	Pre-washed during manufacture-low blank levels for ions. Contains large and variable quantities of Al and Si. Some batches contain other metals. Passively adsorbs organic vapors. Adsorbs little HNO_3, NO_2, and SO_2. Low hygroscopicity.	ICP/AES, ICP/MS, IC, AC, T, TOR, TMO, TOT, OA.

(continued)

Table A2.1 *continued*

Filter Type, (Major Manufacturer)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods
Mix quartz-fiber (Whatman Corp., Hillsboro, OR)	20.3 × 25.4 cm	Quartz (SiO_2) fibers with ~5% borosilicate content. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Some batches can melt at ~500°C. Effects on thermal carbon analysis are unknown. Becomes brittle when heated. Low flow resistance.	High blank weight. Low hygroscopicity. Contains large and variable quantities of Na, Al, and Si in all batches. Variable levels of other metals are found in many batches. Passively adsorbs organic vapors. Adsorbs little HNO_3, NO_2, and SO_2. Low hygroscopicity.	Gravimetry, XRF, PIXE, AA, ICP/AES, ICP/MS for some metals, IC, AC, T, TOR, TMO, TOT.
Cellulose-fiber (Whatman Corp., Hillsboro, OR)	25 mm 37 mm 47 mm	Thick mat of cellulose fibers, often called a "paper" filter. White opaque surface, diffuses transmitted light. Low particle collection efficiencies, < 70% for some variations of this filter. High mechanical strength. Burns at elevated temperatures (~150°C, exact temperature depends on nature of particle deposit). Variable flow resistance.	High purity, low blank levels. Made of carbon-based material, so inappropriate for carbon analysis. Adsorbs gases, especially water vapor. Most appropriate for adsorbing gases such as HNO_3, SO_2, NH_3, and NO_2 when impregnated with reactive chemicals. High hygroscopicity. High blank weight.	Gravimetry, XRF, PIXE, INAA, AAS, ICP/AES, ICP/MS, IC, AC.
Teflon-coated glass-fiber (Pallflex, Putnam, CT)	37 mm 47 mm	Thick mat of borosilicate glass fiber with a layer of Teflon on the surface. Glass fiber supporting Teflon is shiny. High particle collection efficiencies. Glass melts at ~500°C. Teflon melts at ~60°C. Low flow resistance.	Low blank levels for ions (glass backing and carbon content make it less suitable for elemental and carbon analyses). Inert to adsorption of HNO_3, NO_2, and SO_2. Low hygroscopicity. High blank weight.	Gravimetry, IC, AC.

(continued)

Table A2.1 *continued*

Filter Type, (Major Manufacturer)	Filter Size	Physical Characteristics	Chemical Characteristics	Compatible Analysis Methods
Glass fiber (Gelman Scientific, Ann Arbor, MI)	20.3 × 25.4 cm	Borosilicate glass fiber. White opaque surface, diffuses transmitted light. High particle collection efficiencies. Melts at ~500°C. Low flow resistance.	High blank levels. Adsorbs HNO_3, NO_2, SO_2, and organic vapors. Low hygroscopicity. High blank weight.	Gravimetry, OA; XRF, PIXE, INAA; AAS, ICP/AES, IC, AC.

MS = Atomic Absorption Spectrophotometry
AC = Automated Colorimetry
IC = Ion Chromatography
ICP/AES = Inductively-Coupled Plasma with Atomic Emission Spectrophotometry
ICP/MS = Inductively-Coupled Plasma with Mass Spectrophotometry
INAA = Instrumental Neutron Activation Analysis
OA = Optical Absorption or Light Transmission (b~)
OM = Optical Microscopy
PIXE = Proton-Induced X-Ray Emissions
SEM = Scanning Electron Microscopy
T = Thermal Carbon Analysis
TEM = Transmission Electron Microscopy
TMO = Thermal Manganese Oxidation Carbon Analysis
TOR = Thermal/Optical Reflectance Carbon Analysis
TOT = Thermal/Optical Transmission Carbon Analysis
XRD = X-Ray Diffraction
XRF = X-Ray Fluorescence

Source: Chow (1995).

Annex 3 Source Profile Sampling Methods

Hot Exhaust Sampling: In these methods, effluent is extracted from a duct or stack at emission temperatures and drawn through filters.[1] The EPA "Method 201" stack test method is most commonly applied in the US to determine compliance with PM_{10} emission standards. Hot exhaust does not permit the condensation of vapors into particles prior to sampling, and it sometimes interferes with the sampling substrate or container. Hot exhaust samples are not often taken on substrates or in containers amenable to extensive chemical analysis. Even though it is widely used for compliance, hot exhaust sampling is not appropriate for receptor modeling studies.

Diluted Exhaust Sampling: Effluent extracted from a duct is mixed with clean ambient air so that gases can condense on particles. The near-ambient temperature effluent is then drawn through substrates that are analyzed for the desired properties. Diluted exhaust samplers are used for laboratory simulations of emissions from individual sources. Dynamometer simulations use diluted exhaust sampling to estimate emissions for different vehicle types, fuels, and driving conditions. Wood stove, fireplace, and cooking stove emissions can also be simulated by dilution sampling of representatives in a laboratory or field environment.

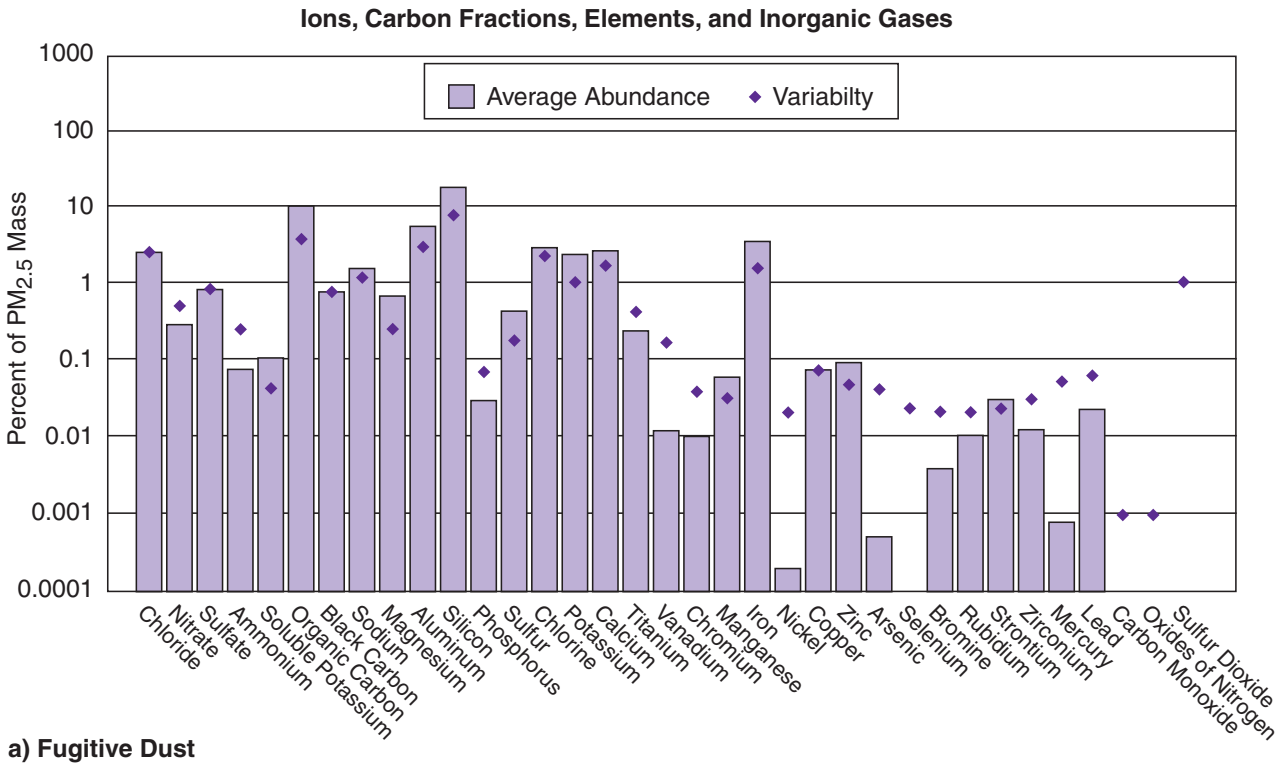
Airborne Sampling: Effluent is drawn from a plume aloft after it has cooled to near ambient temperatures but before it is dominated by the particles present in the background air. Aircraft, balloons, and cranes have been used to elevate sampling systems into the plume. With airborne sampling it is possible to follow a large plume and examine how source profiles change as secondary aerosol is formed. Difficulties of airborne plume sampling are—locating the sampler in the plume instead of ambient air; staying in the plume long enough to obtain a sufficient sample for chemical analysis; mixing of ambient air with the plume, so the source profile is really a combination of emissions and ambient air.

Ground Based Source Sampling: Ambient samples are taken in locations and during time periods for which a single source type dominates the emissions. Ground-based source sampling methods are identical to receptor sampling methods with the requirements that—meteorological conditions and sampling times are conducive to domination by a particular source; samples are of short enough duration to take advantage of those conditions; aerosol from other interfering sources is low or can be apportioned and removed from the sample.

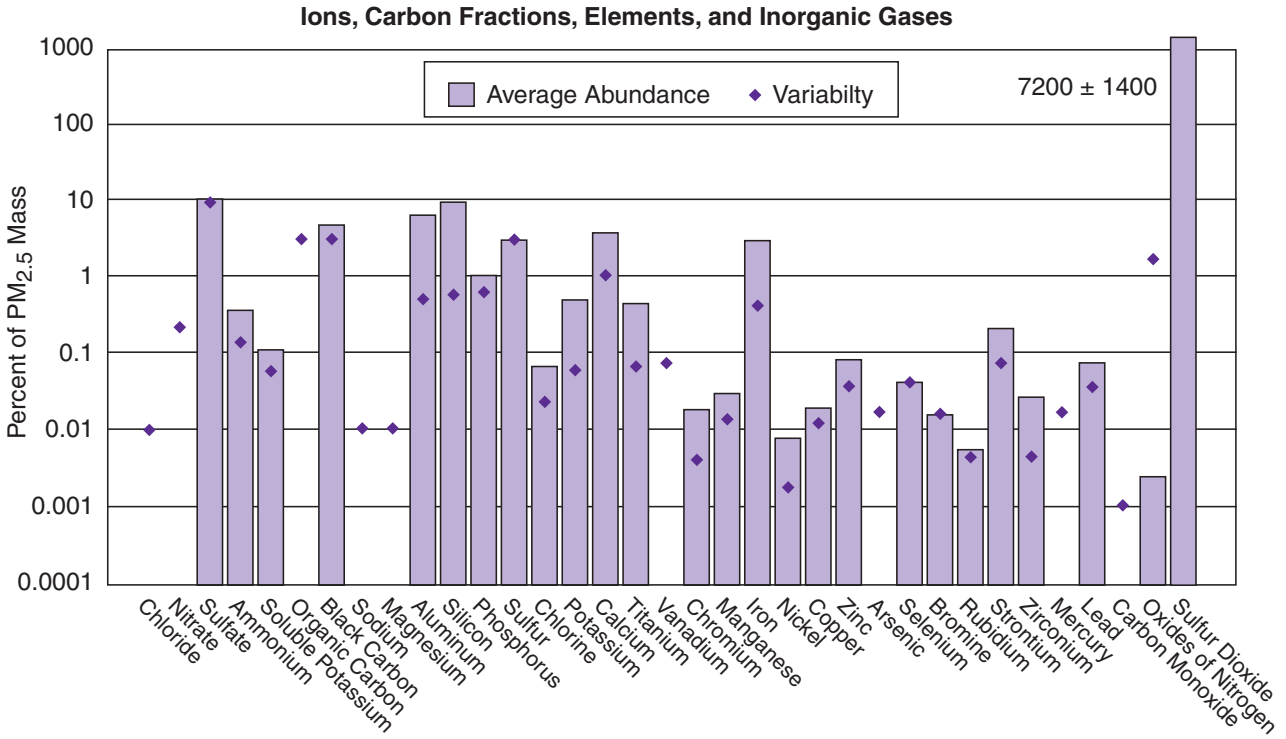
Grab Sampling and Laboratory Resuspension: A sample of pollution residue is obtained and suspended in a chamber for sampling onto filters. This is most applicable to nonducted fugitive and industrial dust emissions. A sample swept, shoveled, or vacuumed from a storage pile, transfer system, or roadbed can be taken to represent these source types. Five to ten different samples from the same source are averaged to obtain a representative source profile. Ground-based and grab sampling are the most cost effective and practical methods for most situations, although large industrial stack emissions require diluted sampling and mobile source sub-types (e.g., high emitting vehicles) can only be isolated in laboratory dynamometer tests.

[1] US EPA methods for point source sampling of PM are available at http://www.epa.gov/ttn/

Figure A3.1 Commonly Measured Elements, Ion, and Organic Markers



a) Fugitive Dust

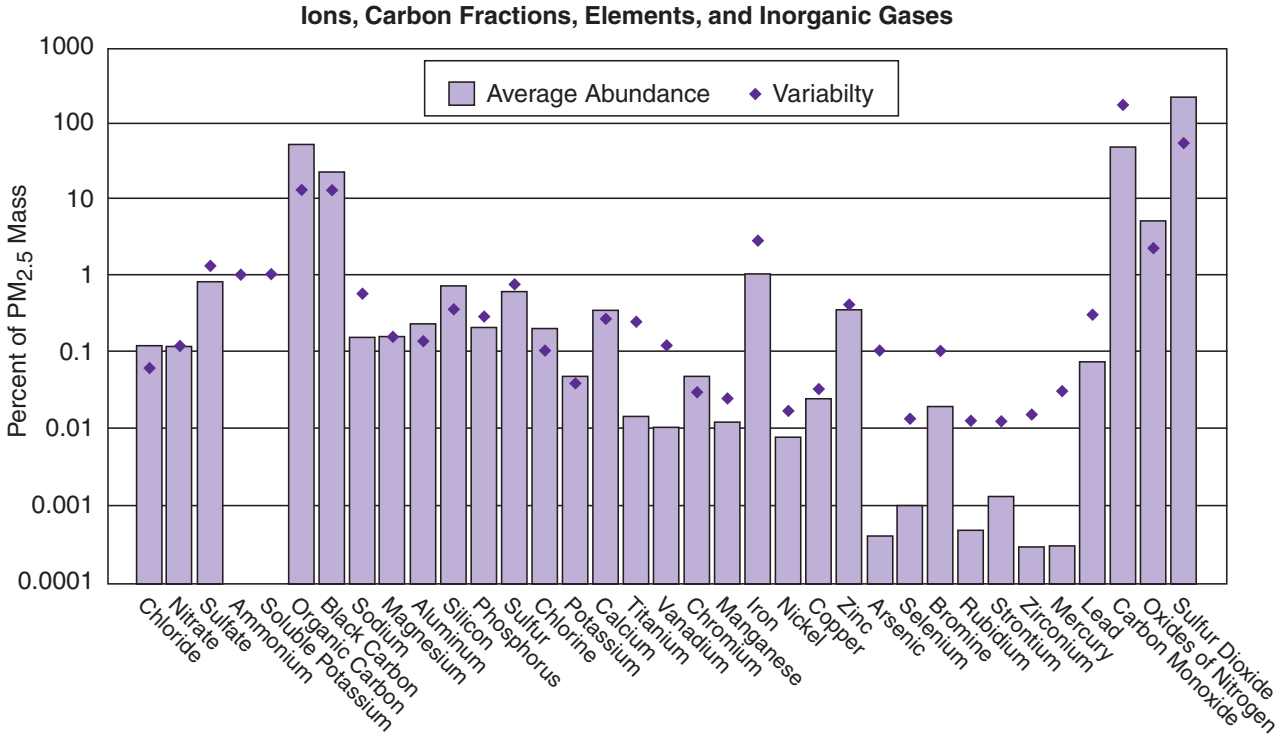


b) Coal-Fired Boiler

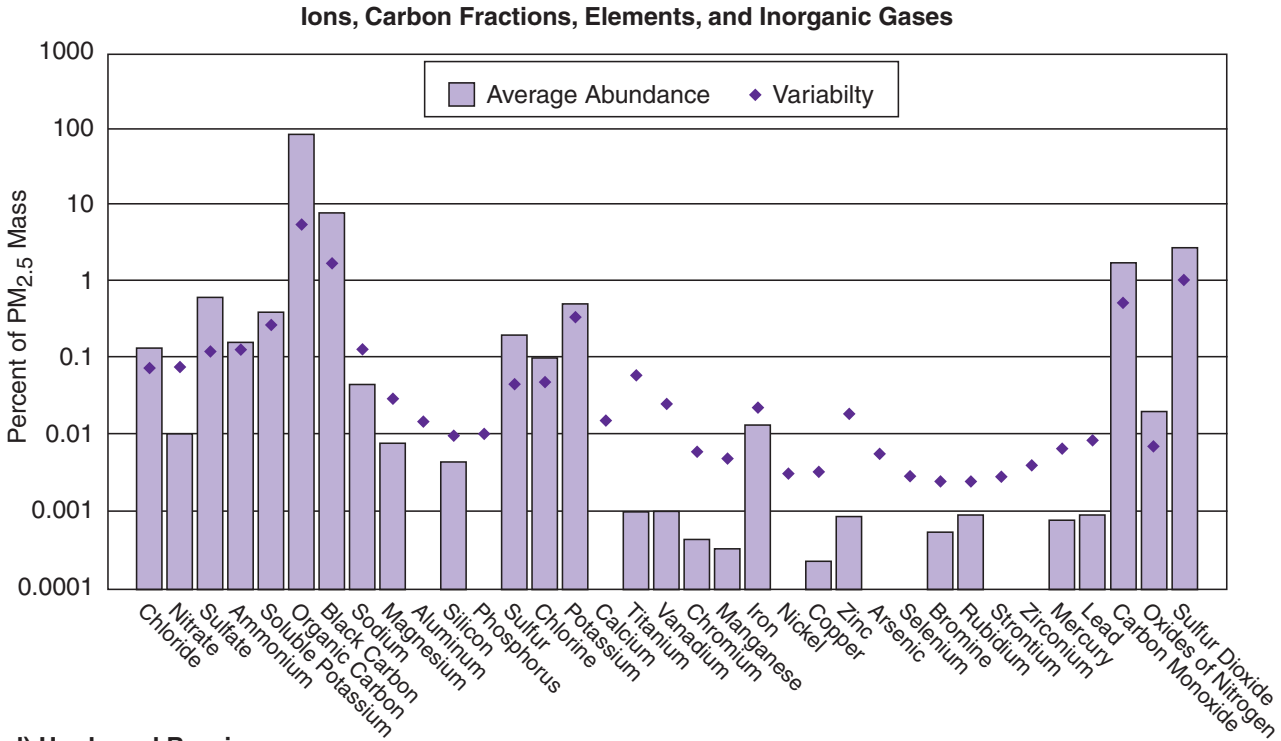
(continued)

Source: Watson and Chow (2007).

Figure A3.1 *continued*



c) Gas Veh. Exhaust

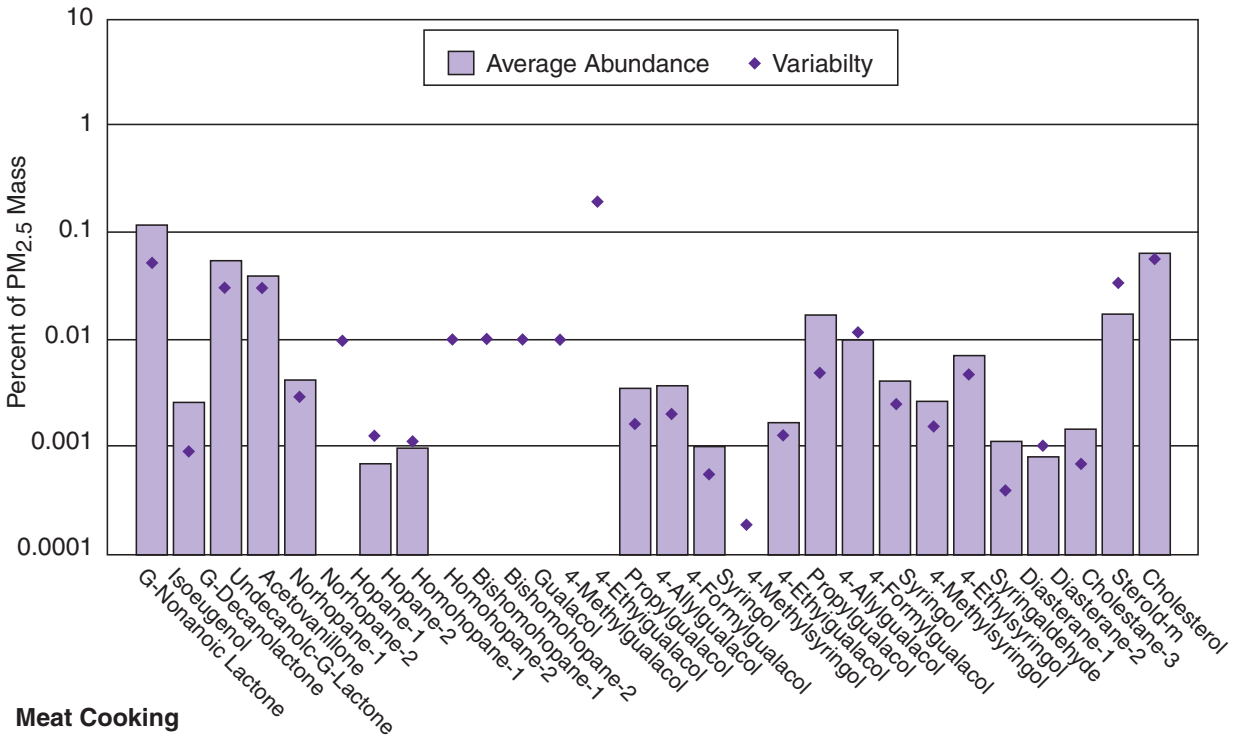


d) Hardwood Burning

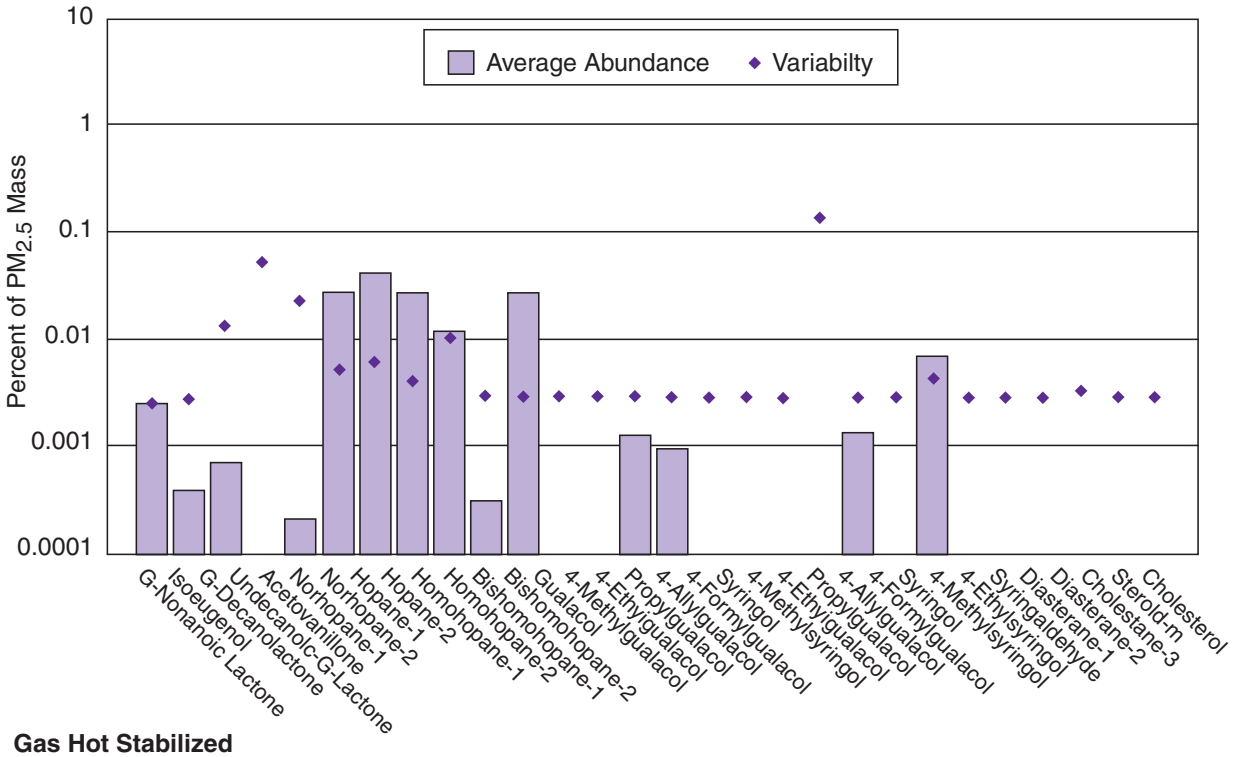
(continued)

Source: Watson and Chow (2007).

Figure A3.1 *continued*



Meat Cooking

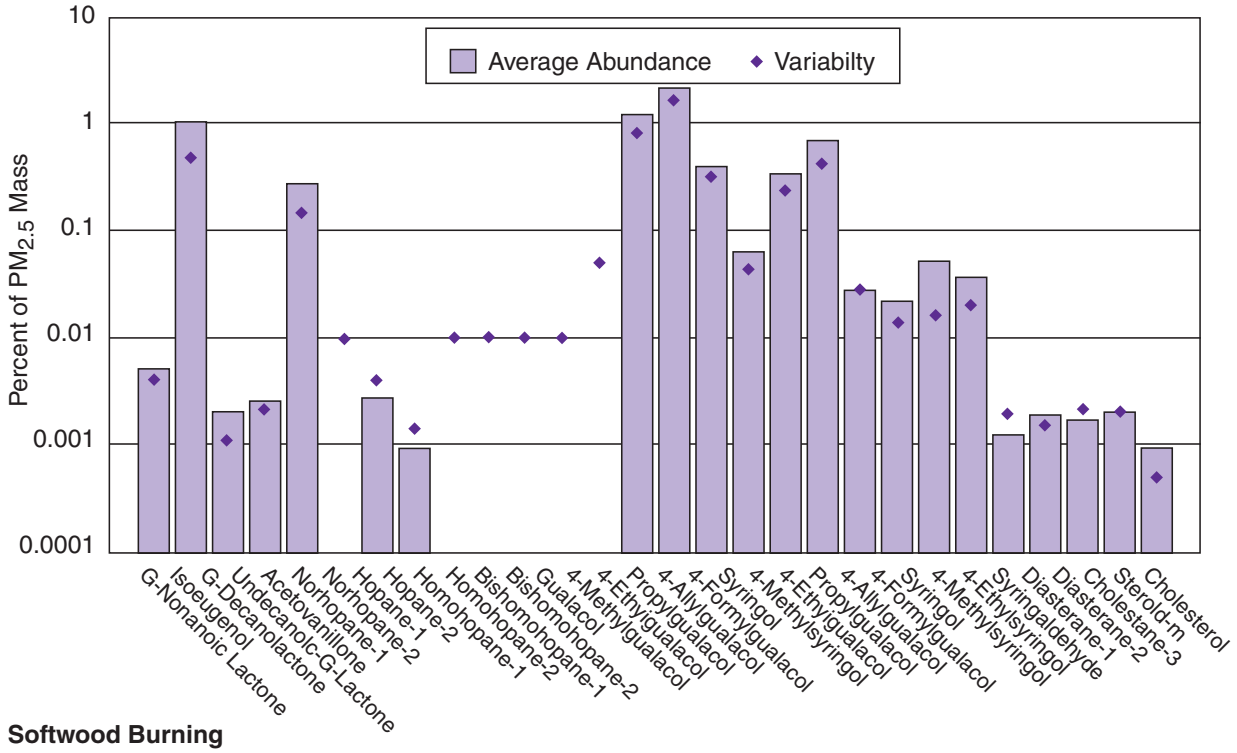


Gas Hot Stabilized

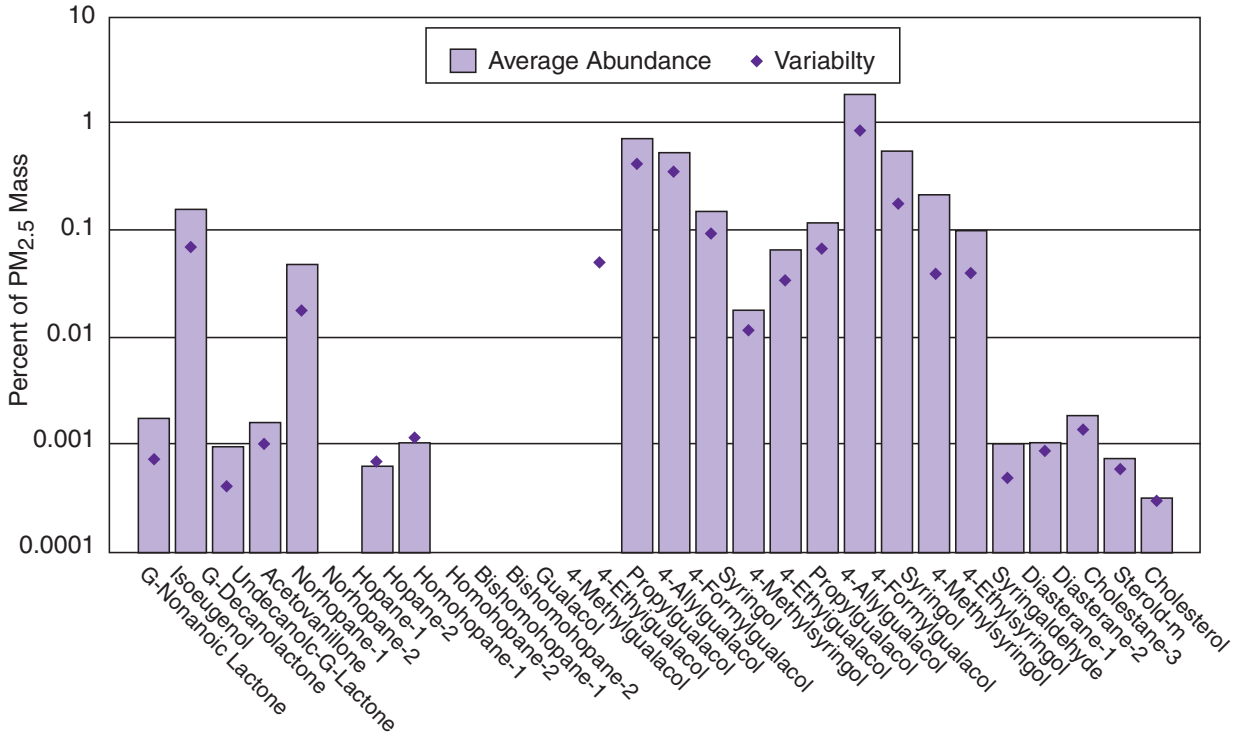
(continued)

Source: Watson and Chow (2007).

Figure A3.1 *continued*



Softwood Burning



Hardwood Burning

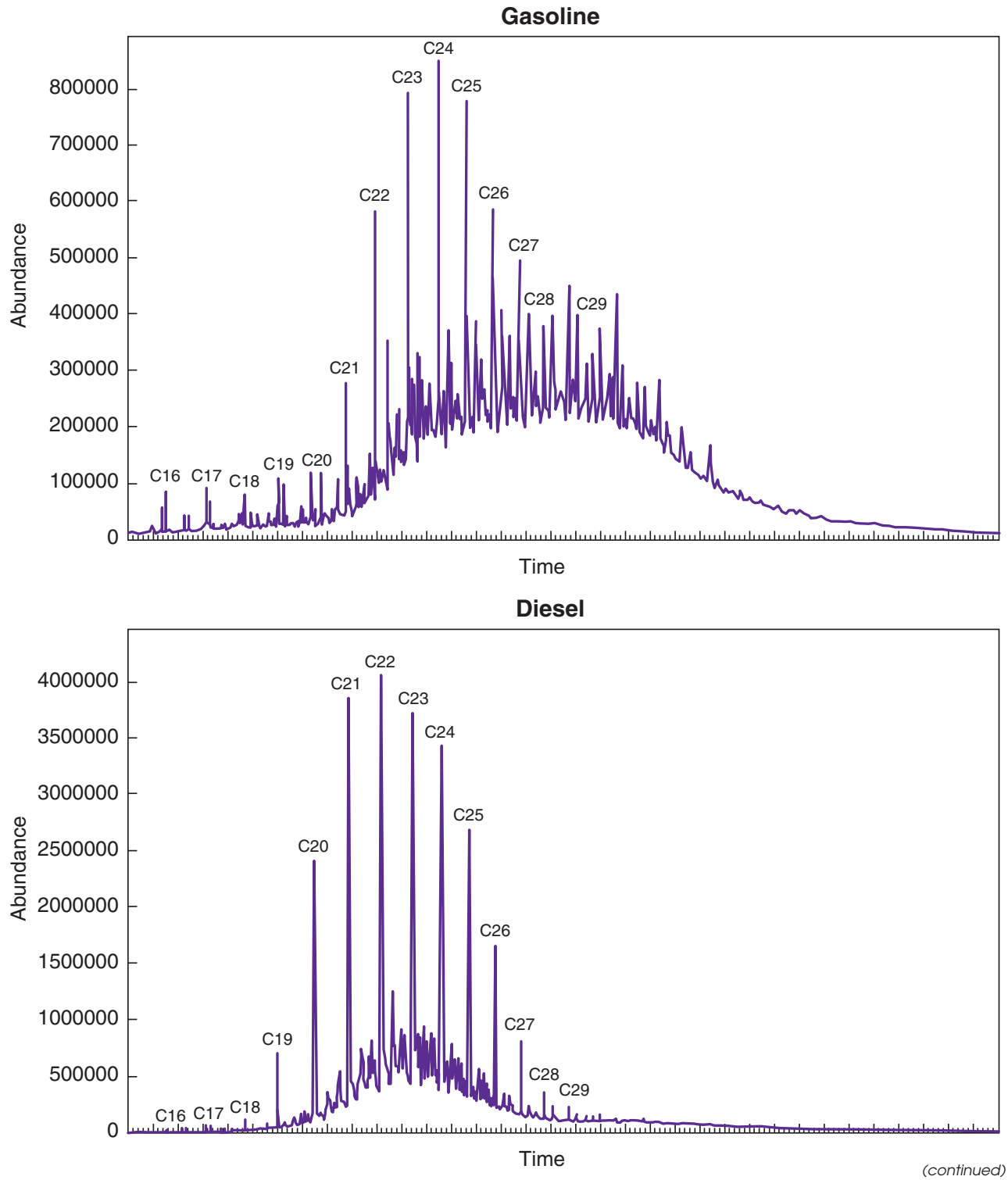
Source: Watson and Chow (2007).

Table A3.1 Source Profiles for Shanghai, China

SID	Watered Dust Removal for Coal-burned Boiler	Cyclone Dust Removal for Coal-burned Boiler	Heavy Oil Boiler	Boiler for Power Plant	Cement-Kiln Mill	Electric Cooker for Ferroalloy	Coking	Road Dust	Vehicle Exhaust	Soil
NO_3^-	0.325	0.085	2.7	0.02	0.425	1.8	0.957	0.81	58	0.9
SO_4^{2-}	245	48	11	8.08	19.95	14.9	34.893	0.09	18.3	0.9
NH_4^+	1.65	0.835	–	5.24	6.89	8.76	–	–	3.26	0.9
Na	6.42	1.795	28.3	1.1	14.7	19.7	11.833	11.3	10.5	9.32
EC	–	–	–	–	–	–	–	–	–	–
OC	–	–	–	–	–	–	–	–	–	–
Al	4.805	11.75	13.7	13.3	13.5	4.83	10.543	7.2	2.25	79.4
Cl	0.055	0.575	37	0	0.075	0.31	161.8	8.71	27	9
K	2.98	1.091	3.67	0.816	2.243	2.22	1.76	0.1	8.52	23.4
Ca	10.42	4.605	51.4	2.54	26.97	12.9	14.137	83.6	23.5	9.87
Ti	0.676	2.67	2.17	1.3	1.735	0.222	1.086	0.45	0.05	5.2
Cr	0.1565	0.072	0.01	0.067	0.0385	1.11	0.405	0.275	0.05	0.09
Mn	0.1295	0.047	0.75	0.214	0.482	1.33	0.675	0.425	0.38	1.08
Fe	11.94	7.315	36.6	12.4	24.5	24.2	20.367	14.3	13.3	40.88
Ni	0.2955	0.1035	0.01	0.083	0.0465	0.611	0.247	0.01	0.9	0.2
Cu	0.823	0.5615	0.25	0.102	0.176	0.01	0.096	0.225	0.32	0.08
Zn	2.045	1.749	9.25	0.132	4.691	19	7.941	2.03	2.5	0.4
Pb	1.023	1.56	0.01	0.036	0.023	1.5	0.52	0.1	0.43	0.28
Mg	1.79	0.9725	9	2.8	5.9	20.5	9.733	8	6.01	1.21
As	0.22	0.3185	1.3	0.077	0.6885	0.1	0.289	0.1	0.001	0.1
Se	0.1	0.2	0.1	0.157	0.1285	0.1	0.129	0.1	0.01	0.09
Ba	2.733	4.09	10.2	0.456	5.328	2.39	2.725	2.98	0.33	0.09
Sr	2.73	9.905	1.92	5.13	3.525	1.83	3.495	3.2	0.05	0.09
F	2.31	1.125	20.18	0.56	2.795	31.79	10.923	0.09	0.73	0.09
Si										299.7

Source: Shanghai Academy of Environmental Sciences, Shanghai, China.

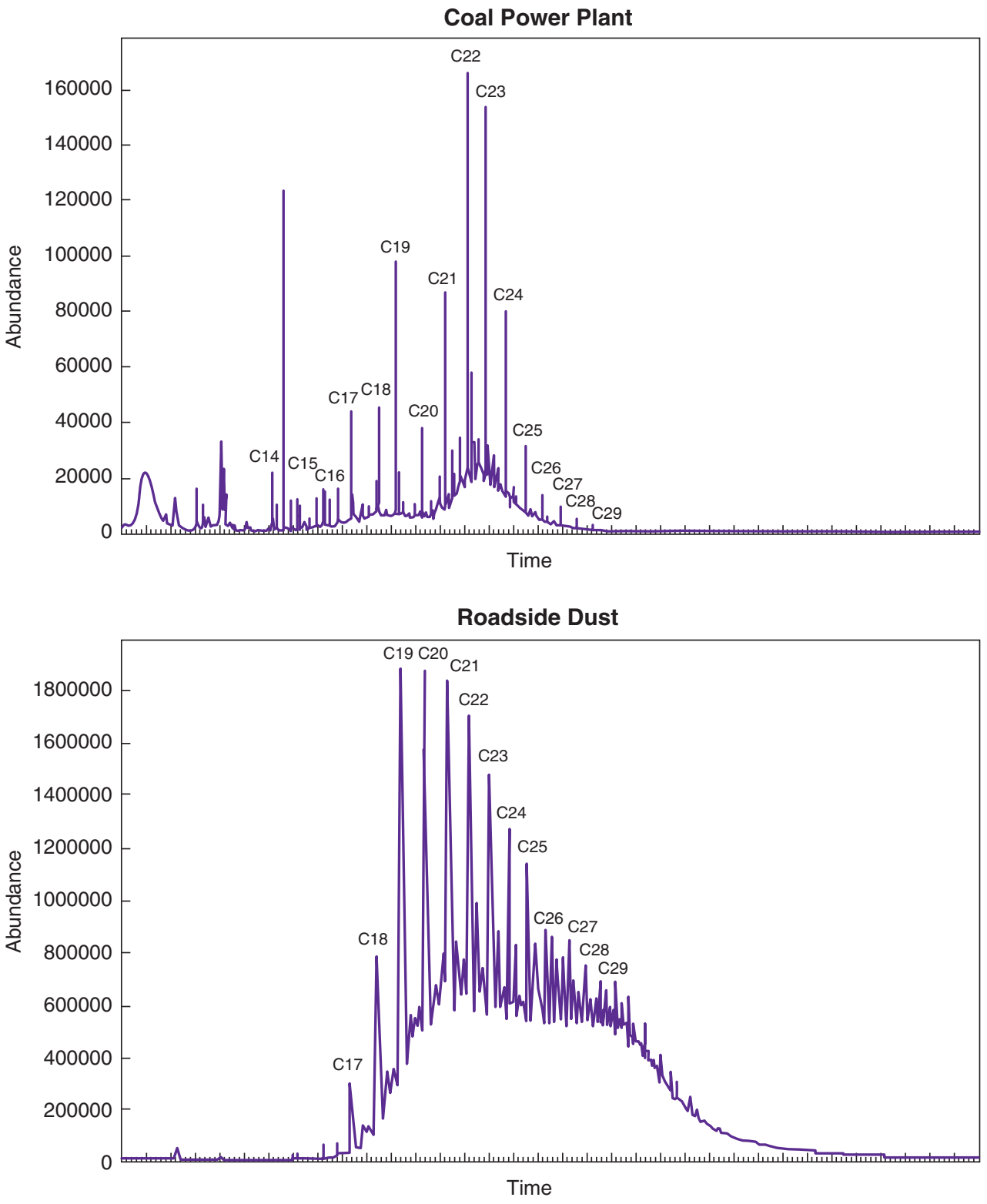
Figure A3.2 Examples of Organic Source Profiles Using Smaller Samples



(continued)

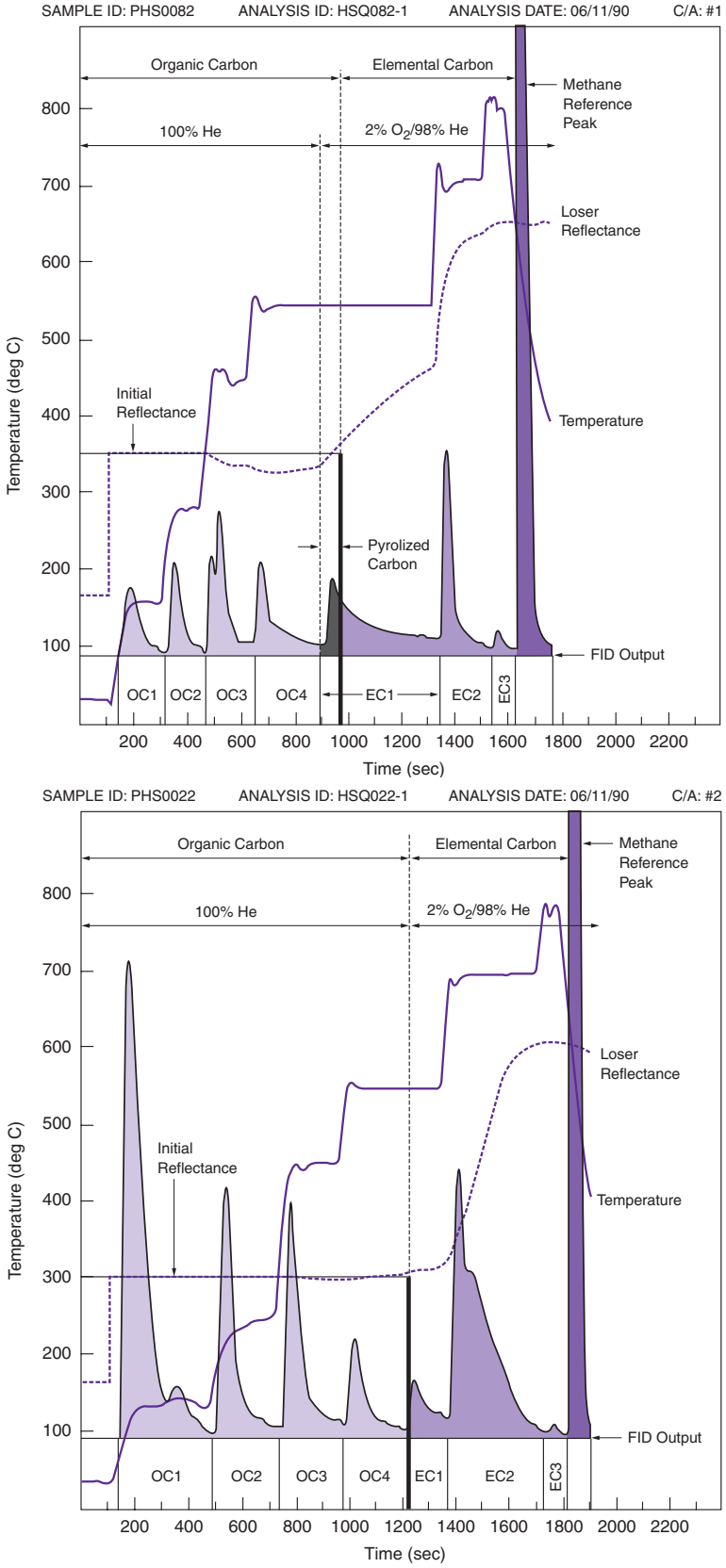
Source: Watson and Chow (2007).

Figure A3.2 *continued*



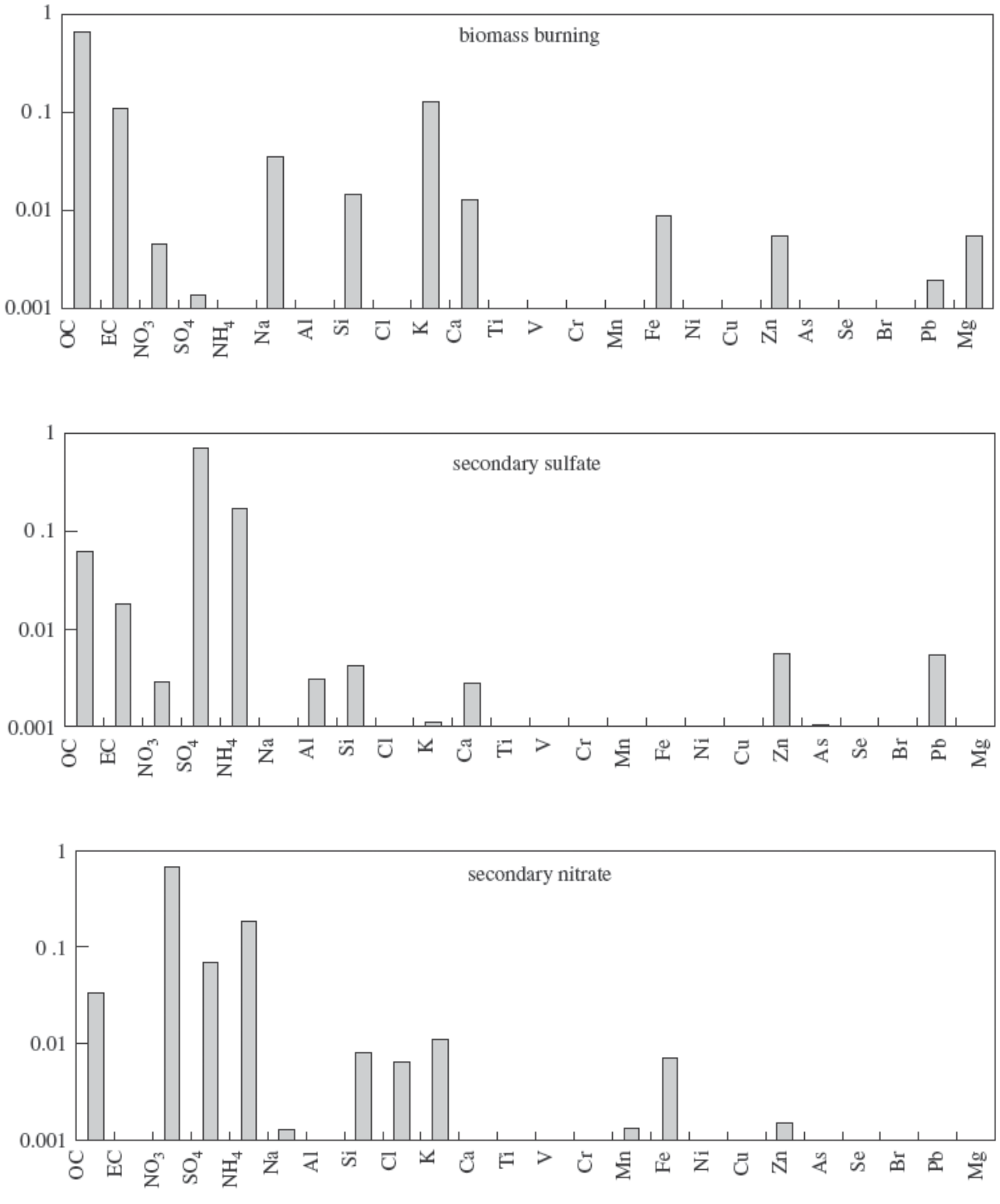
Source: Watson and Chow (2007).

Figure A3.3 Thermally Evolved Carbon Fractions for (a) Gasoline Fueled Vehicles (b) Diesel Fueled Vehicles



Source: Watson et al., (1994).

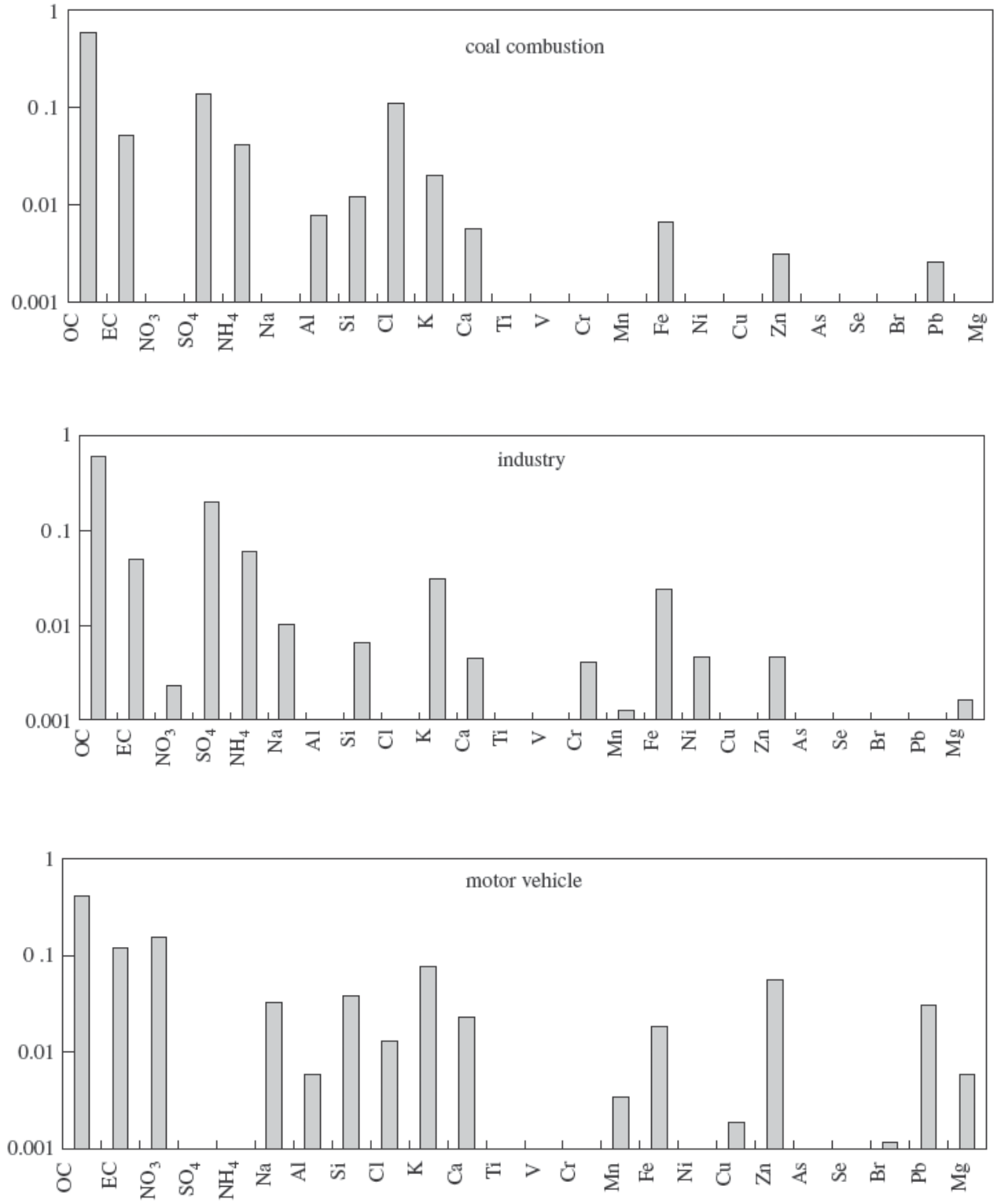
Figure A3.4 Source Profiles for Beijing, China



(continued)

Source: Song et al., (2006).

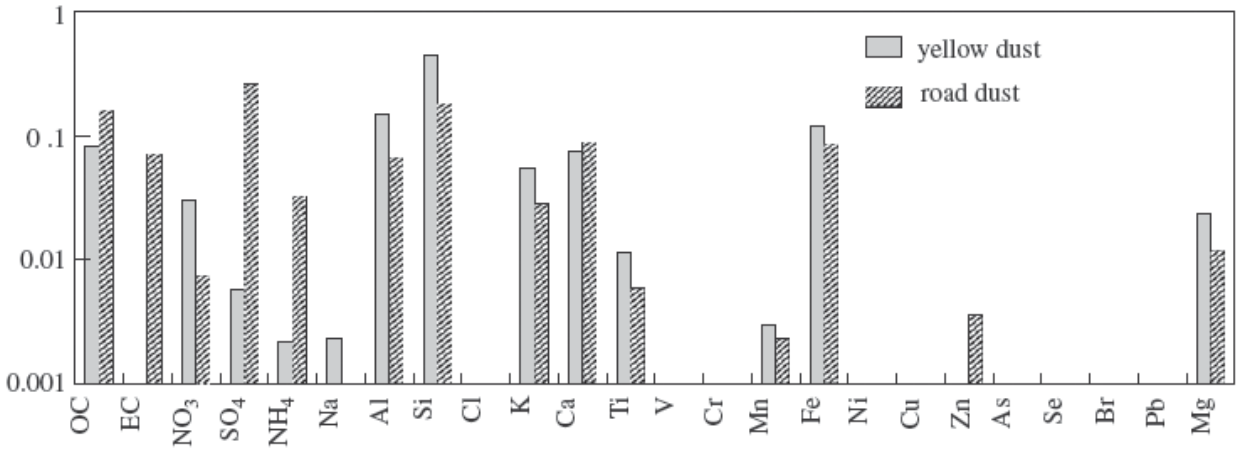
Figure A3.4 *continued*



(continued)

Source: Song et al., (2006).

Figure A3.4 *continued*



Source: Song et al., (2006).

Annex 4 Minimum Detection Limits of Elements on Measured Samples

Table A4.1 Minimum Detection Limits of Elements on Measured Samples

	Minimum Detection Limit in ng/m³ [58]					
Elements	**ICP/AES[59]**	**AA/Flame[42]**	**AA/Furnace[42]**	**INAA[42]**	**PIXE**	**XRF[60]**
Be	0.06	2	0.05	NAd	NA	NA
Na	NA	0.2	< 0.05	2	60	NA
Mg	0.02	0.3	0.004	300	20	NA
Al	20	30	0.01	24	12	5
Si	3	85	0.1	NA	9	3
P	50	100,000	40	NA	8	3
S	10	NA	NA	6,000	8	2
Cl	NA	NA	NA	5	8	5
K	NA	2	0.02	24	5	3
Ca	0.04	1	0.05	94	4	2
Sc	0.06	50	NA	0.001	NA	NA
Ti	0.3	95	NA	65	3	2
V	0.7	52	0.2	0.6	3	1
Cr	2	2	0.01	0.2	2	1
Mn	0.1	1	0.01	0.12	2	0.8
Fe	0.5	4	0.02	4	2	0.7
Co	1	6	0.02	0.02	NA	0.4
Ni	2	5	0.1	NA	1	0.4
Cu	0.3	4	0.02	30	1	0.5
Zn	1	1	0.001	3	1	0.5
Ga	42	52	NA	0.5	1	0.9
As	50	100	0.2	0.2	1	0.8
Se	25	100	0.5	0.06	1	0.6

(continued)

[58] Minimum detection limit is three times the standard deviation of the blank for a filter of 1 µg/cm² area density.

[59] Concentration is based on the extraction of 1/2 of a 47 mm filter in 15 ml of deionized-distilled water, with a nominal flow rate of 20 l/min for 24-hour samples.

[60] Concentration is based on 13.8 cm2 deposit area for a 47 mm filter substrate, with a nominal flow rate of 20 l/min for 24-hour samples with 100s radiation time.

Table A4.1 *continued*

Br	NA	NA	NA	0.4	1	0.5
Rb	NA	NA	NA	6	2	0.5
Sr	0.03	4	0.2	18	2	0.5
Y	0.1	300	NA	NA	NA	0.6
Zr	0.6	1000	NA	NA	3	0.8
Mo	5	31	0.02	NA	5	1
Pd	42	10	NA	NA	NA	5
Ag	1	4	0.005	0.12	NA	6
Cd	0.4	1	0.003	4	NA	6
In	63	31	NA	0.006	NA	6
Sn	21	31	0.2	NA	NA	8
Sb	31	31	0.2	0.06	NA	9
I	NA	NA	NA	I	NA	NA
Cs	NA	NA	NA	0.03	NA	NA
Ba	0.05	8	0.04	6	NA	25
La	10	2000	NA	0.05	NA	30
Au	2.1	21	0.1	NA	NA	2
Hg	26	500	21	NA	NA	1
Ti	42	21	0.1	NA	NA	1
Pb	10	10	0.05	NA	3	1
Ce	52	NA	NA	0.06	NA	NA
Sm	52	2000	NA	0.01	NA	NA
Eu	0.08	21	NA	0.006	NA	NA
Hf	16	2000	NA	0.01	NA	NA
Ta	26	2000	NA	0.02	NA	NA
W	31	1000	NA	0.2	NA	NA
Th	63	NA	NA	0.01	NA	NA
U	21	25,000	NA	NA	NA	1

Source: Landsberger and Creatchman (1999).

ICP/AES = Inductively Coupled Plasma with Atomic Emission Spectroscopy.

AA = Atomic Absorption Spectro-photometry.

PIXE = Proton Induced X-ray Emissions Analysis.

XRF = X-ray Fluorescence Analysis.

INAA = Instrumental Neutron Activation Analysis.

NA = Not available.

Annex 5 Questionnaire for Source Apportionment Case Studies

Background—General background of the city and project:

- What is the city, its size, the main economic activities, etc.?
- Who are the principle investigator(s)?
- What were the lead institution(s)?
- When was the research undertaken and for how long?

Basic project information—Information on the basic objectives of the project:

- What were the main objectives of the study?
- What kinds of assumptions were made?
- Which local partners where involved in the project?

Project Costs—Description of the costs and sources of funding:

- What were the total project costs?
- What were the funding sources?
- What were the man hours spent on the project?
- How much was spent on local expertise?
- What were the local vs. other costs?
- What was spent on equipment, material and maintenance? Please specify?
- What was the cost of analyzing the samples? Where was it done?

Measurement sites—Describe the measurement sites and their surroundings:

- Where did you measure?
- How did you characterized road, residential, industrial, etc.?
- Why these sites were chosen?
- How representative are these sites for the entire city?

Measurement Methodology—Detailed explanation of sampling methodology and analysis:

- How often and for how long were samples taken?
- During what period of the year and what were the locations?
- What were the total numbers of (usable) samples?
- What kind of sampling methodology was used? Which filter was used?
- What subsequent analysis was used for source apportionment and where was this done?
- Was there any quality control of the data?
- Were other alternative sampling methods considered and/or used? Which and why used or not?

Source Characteristics—Describe the main sources and their chemical characteristics:

- What are the main sources and how were the different sources characterized?
- Was there an emission inventory database (bottom-up)?
- How was the information gathered and verified?

Outcomes—What were the main finding of the source apportionment study:

- What were the major findings?
- What are the main sources of fine particulate matter?
- Were the results much different from "expected" results? Explain.

- Were the findings mostly for academic use or also used for policy discussions and policy making?
- What are the main challenges and uncertainties that remain?

Lessons learned—Describe the main lessons learned and recommendations for future studies:

- How applicable are the applied methodology / techniques for other cities?
- How useful are the results for decision making and actual use by policy makers?
- What is the local capacity in assisting in the planning and diagnosis of similar projects?
- Is the program replicable to other cities?

Annex 6 Resources to Emission Inventory

Resource Links

Global Emissions Inventory Activity (GEIA)—http://geiacenter.org/

EDGAR Information System—http://www.mnp.nl/edgar/new/

Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)—http://www.iiasa.ac.at/rains/gains

Regional Air Pollution Information and Simulation (RAINS-Asia)—http://www.iiasa.ac.at/~rains/asia2/

South Africa (SAFARI 2000)—http://www-eosdis.ornl.gov/S2K/safari.html

International Global Atmospheric Chemistry (IGAC)—http://www.igac.noaa.gov/

Ace-Asia Emissions Support System (ACESS)—http://www.cgrer.uiowa.edu/ACESS/acess_index.htm

Clearinghouse for Inventories & Emissions Factors (USEPA—Chief)—http://www.epa.gov/ttn/chief/

BC Inventory by Tami Bond (A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res.*, *109*, D14203, doi:10.1029/2003JD003697).

Climate Analysis Indicators Tool (CAIT)—http://cait.wri.org/

CO-oRdinated INformation on the Environment in the European Community—AIR (CORINAIR)—http://www.aeat.co.uk/netcen/corinair/94/

Energy Information Administration (EIA)—http://eia.doe.gov/

Center for Air Pollution Impact and Trend Analysis (CAPITA)—http://capita.wustl.edu/CAPITA/

Convention on Long-range Transboundary Air Pollution (EMEP)—http://www.emep.int/

United Nations Framework Convention on Climate Change (UNFCCC)—http://ghg.unfccc.int/

Clean Air Initiatives—http://www.cleanairnet.org/

Case Study of Asian Megacities

An emission inventory for Asian cities is discussed below. Table A6.1 presents city-specific emission estimates for Asia in 2000. Of the total anthropogenic emissions in Asia, megacities account for 13% of SO_2 (5.5 Tg SO_2/year), 12% of NO_x (3.3 Tg NO_2/yr), 11% of CO (18.7 Tg CO/yr) (excluding biomass burning emissions), 13% of VOC's (6.68 Tg C/yr), 13% of BC (0.26 Tg C/yr) (excluding biomass burning emissions), 14% of OC (1.0 Tg C/yr) (excluding biomass burning emissions), 16% of PM_{10} (4.4 Tg PM/yr) and $PM_{2.5}$ (3.4 Tg PM/yr) in the base year 2000. While the megacity emissions account for 10-15% of total Asian anthropogenic emissions, they are concentrated into ~2% of the land area, leading to a very high emission density. Furthermore, 30% of the Asian population resides in these cities; thus megacity emissions project a disproportionate impact on human health. The geographical location of these cities, most of which are coastal cities, plays an important role in determining how the pollutants are dispersed.

The group of cities selected in this study range from cities dominated by transport related

Table A6.1 Primary Emission Estimates (ktons) for Asian Cities in 2000

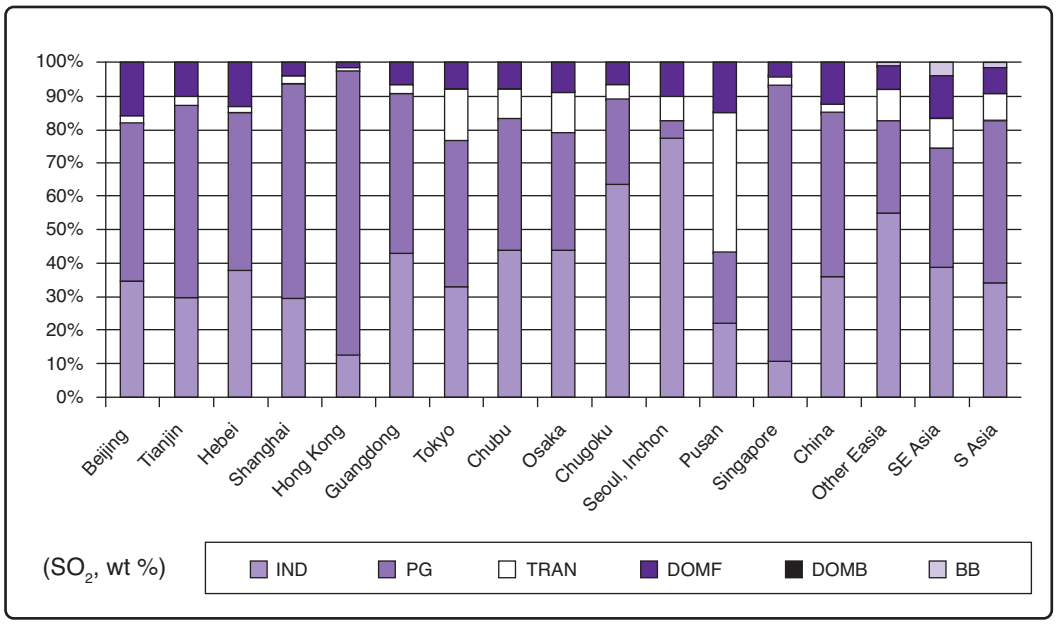
	SO_2	NO_x*	VOC	CO	BC	OC	PM_{10}	$PM_{2.5}$
East Asia								
Beijing	238.0	118.1	225.6	1237.0	8.6	13.1	83.2	42.7
Taiyuan	178.3	52.1	55.5	329.6	4.0	3.8	28.5	11.0
Tianjin	200.7	152.6	198.8	973.1	8.1	12.8	70.4	35.7
Shanghai	250.8	222.4	348.3	1716.1	7.6	11.8	79.9	42.6
Qingdao	23.9	17.1	27.8	148.9	1.2	3.9	11.5	9.5
Guangzhou	97.2	63.3	120.0	390.6	2.7	7.5	29.6	20.9
Wuhan	93.9	56.3	115.8	594.9	10.3	30.4	95.2	73.7
Chongqing	150.5	31.9	83.3	463.4	7.8	24.4	71.4	58.1
Hong Kong	36.1	99.8	133.1	270.5	1.3	2.5	17.2	12.1
Seoul	309.9	400.9	282.1	254.1	7.0	9.0	46.9	24.0
Pusan	55.7	97.3	183.0	133.6	1.0	0.8	13.3	6.6
Tokyo	112.3	276.2	414.5	461.1	5.7	6.5	31.7	18.3
Osaka	83.1	176.7	197.6	330.2	4.1	4.7	24.3	14.9
S.E. Asia								
Bangkok	162.4	58.2	235.6	213.2	3.9	15.5	67.5	55.5
Singapore	188.7	213.7	153.7	158.2	3.9	5.1	266.0	165.4
Jakarta	97.4	66.6	671.3	1210.1	21.2	102.8	298.4	281.6
Manila	113.4	26.0	123.7	59.0	2.9	12.0	39.5	35.8
Kuala Lumpur	54.3	48.2	157.6	101.9	1.8	5.8	30.0	20.4
South Asia								
Calcutta	65.2	61.6	233.0	631.3	16.1	76.7	345.3	273.0
New Delhi	69.7	64.6	181.8	598.8	7.4	32.4	223.2	152.3
Bombay	46.3	24.8	61.0	113.4	3.0	12.8	59.5	43.5
Karachi	155.1	25.0	40.7	47.9	4.4	18.5	95.2	72.1
Lahore	93.2	32.4	88.8	254.3	6.4	28.4	155.5	117.3
Dhaka	20.3	14.1	73.5	380.5	6.3	30.9	118.3	100.2

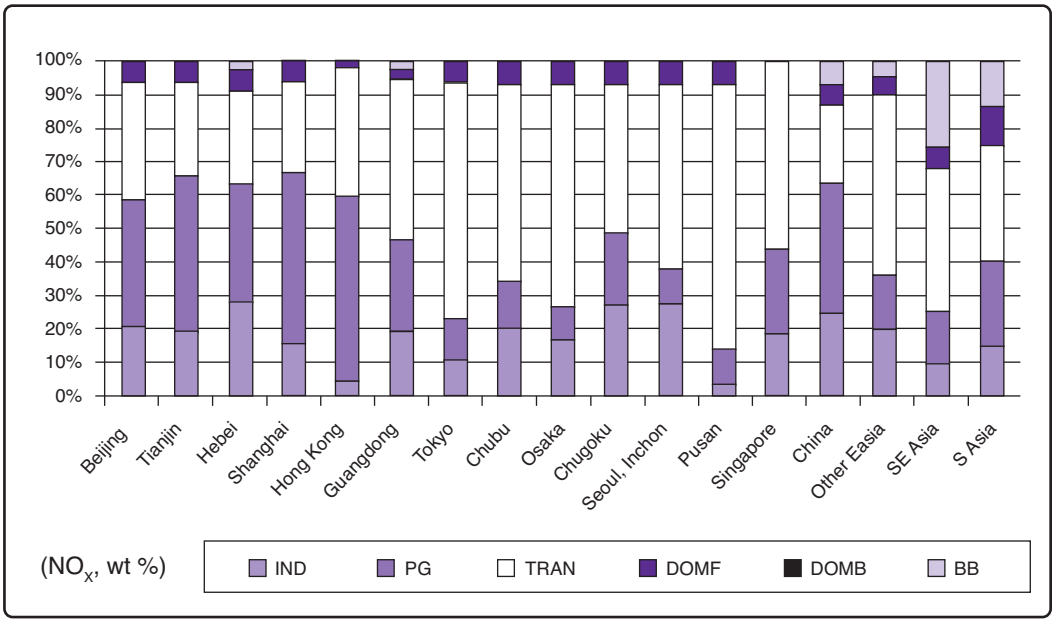
Source: Guttikunda, et al. (2005) and Streets et al. (2003).

emissions (e.g., Tokyo, Seoul, Shanghai) to cities with coal based technologies (e.g., Beijing and Dhaka). Figure A6.2 presents the sectoral contribution to various pollutant emissions.

- For SO_2, industry (IND) and power generation (PG) account for ~80% of the emissions in Asian cities. Tokyo, Osaka and Pusan are the exceptions. Pusan is the only city with >40% of the SO_2 emissions originating from the transport sector (TRAN). This is primarily due to the use of high sulfur diesel for shipping and road transport. Otherwise, TRAN contributes less than 5% to the SO_2 emission inventory in Asian cities.
- For NO_x, IND, PG and TRAN dominate the inventory, with the transport sector accounting for as much as 60% in Pusan, Tokyo and Singapore.
- For CO, IND and TRAN dominate the inventory, with domestic bio-fuels (DOMB) contributing significantly in the rural areas of

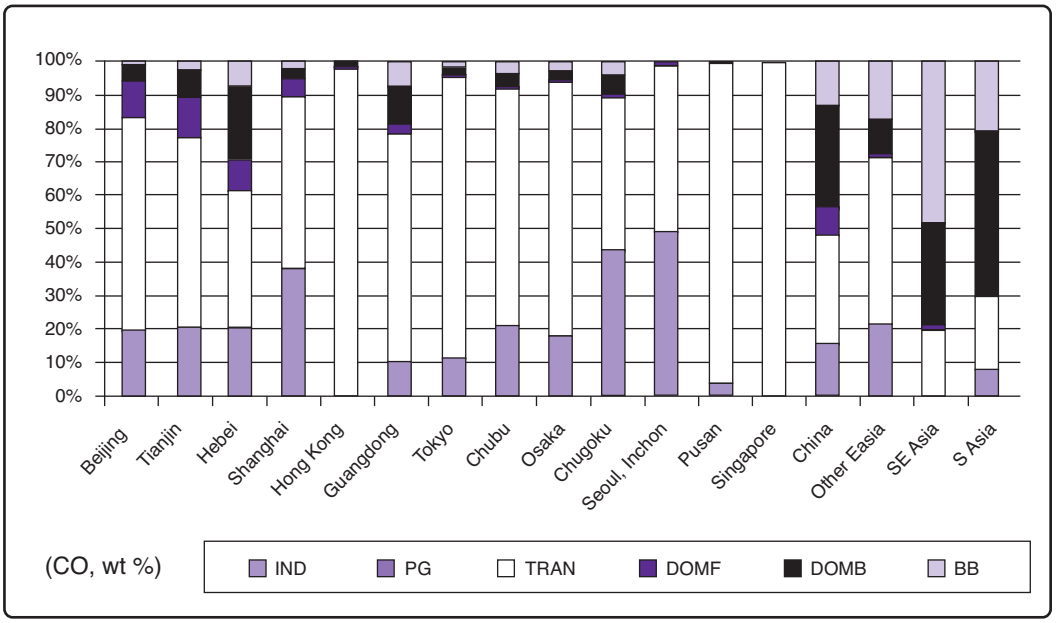
Figure A6.1 Sectoral Contribution to Urban Primary Emission Inventory for 2000

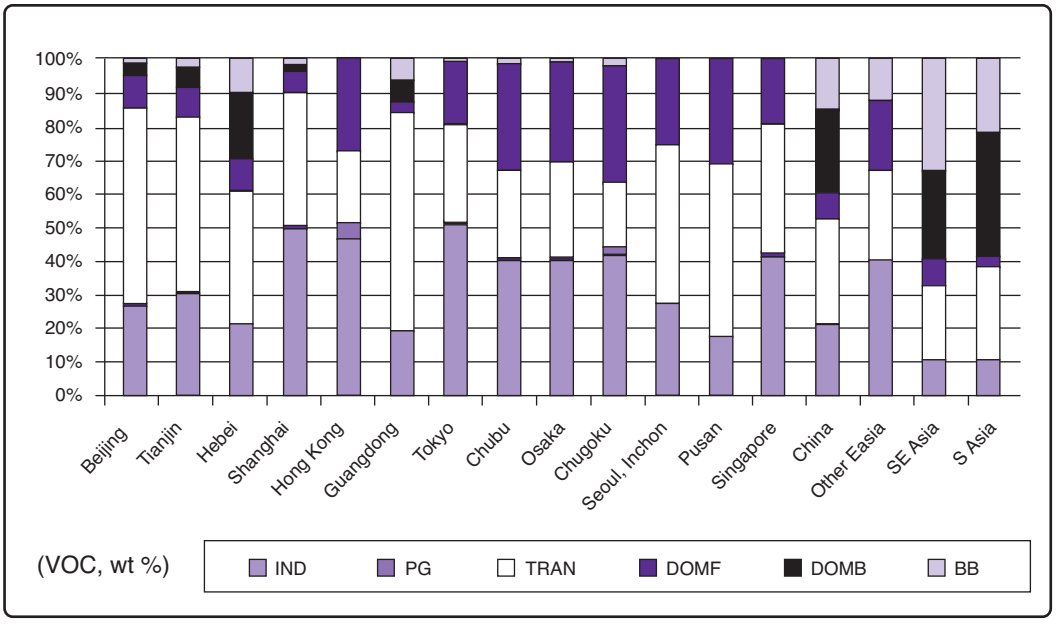




(continued)

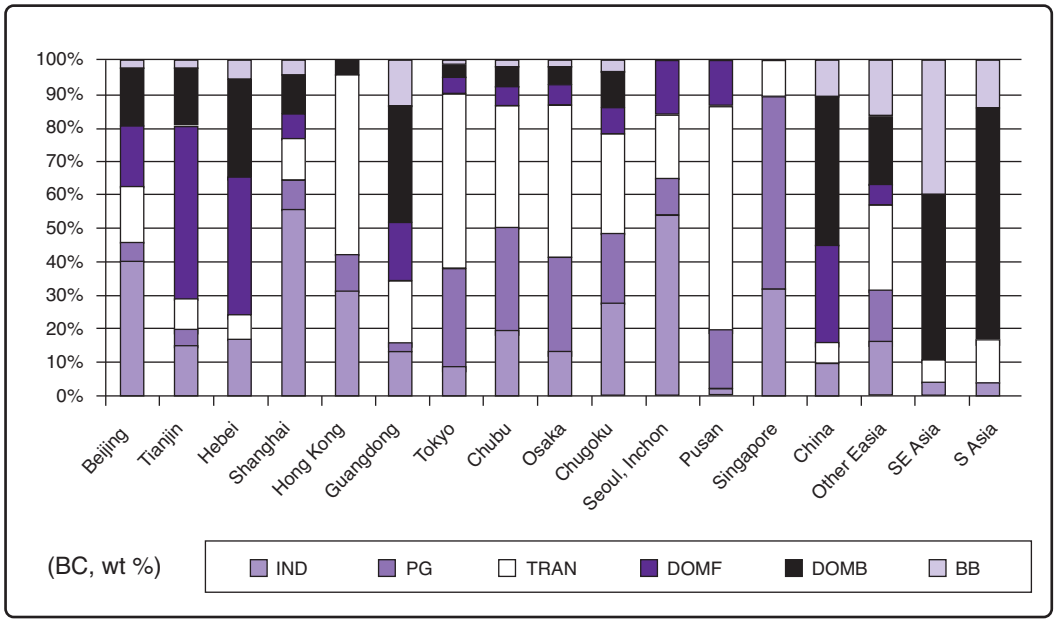
Figure A6.1 *continued*

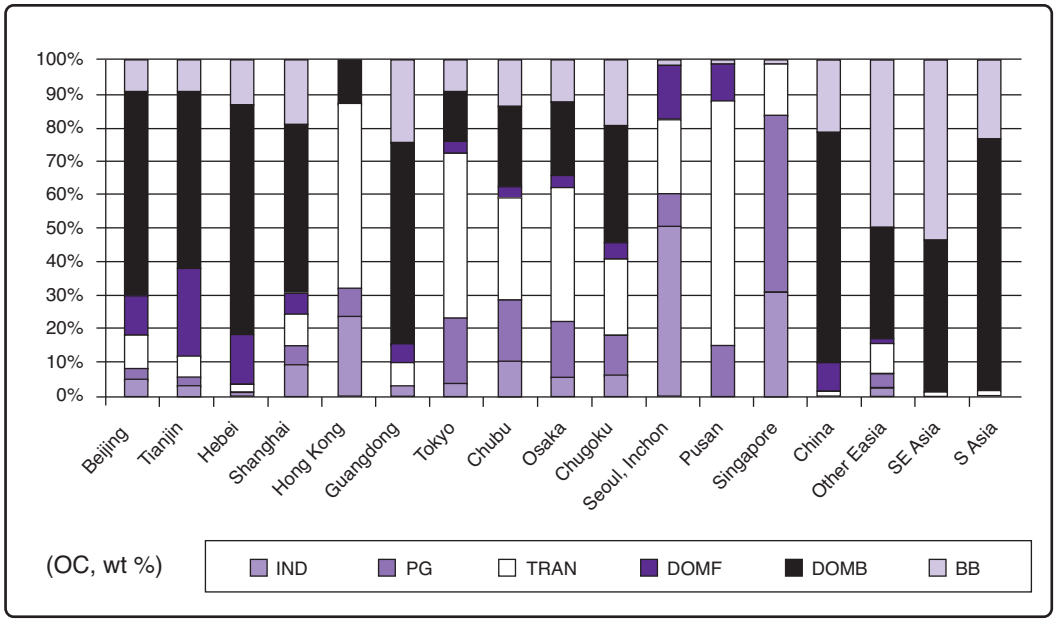




(continued)

Figure A6.1 *continued*





Source: Guttikunda, et al. (2005) and Streets et al. (2003).

Note: IND = Industry; DOMB = Domestic Biofuels; DOMBF = Domestic Fossils; TRAN = Transportation; PG = Power Generation; BB = Biomass Burning.

Southeast and South Asia. Here the domestic sector consists of residential fuel usage and is divided into two parts—emissions due to bio-fuel usage (DOMB) and fossil fuel usage (DOMF). While most of the East Asian cities have >50% of their CO emissions originating from TRAN, Hong Kong and Singapore have TRAN contributions approaching 100%.

- For carbonaceous particles, domestic fossil (DOMF) for the BC, and DOMB for OC, are dominant sources. TRAN is important in the Northeast Asian cities and IND is important in China.
- For NMVOC emissions, IND and TRAN are important in the cities of China, and IND, TRAN and DOMF are important in the Northeast Asian Cities. Besides industrial activity and evaporative sources, domestic coal and bio-fuel combustion contribute to NMVOC emissions in many Asian cities.
- On a broader perspective, biomass burning contributes between 10–20% of the primary trace gas and carbonaceous emissions in Asia megacities.

Differences in the primary energy mix in Asia cities are partially explained by the endowment of energy resources. Asia has 33 percent of world coal reserves, sufficient for more than 100 years of consumption and these reserves are highly concentrated in China, India and Indonesia. Hence, the high dependency on coal as a primary energy source in the power, industrial and domestic sectors. Use of locally available high sulfur coal for domestic cooking and heating, small scale industrial boilers and power sector is the main reason why the SO_2 to NO_x emission ratios are high in cities in China, Southeast Asia, and the Indian Subcontinent. This wide range of values reflects cities with energy reforms in transition and a breadth of sulfur control programs. Due to an aggressive shift in the energy mix from coal to oil and gas in South Korea and Japan, implementation of strict sulfur control technologies, and a relatively higher level of vehicular emissions (especially NO_x), cities in these countries have a lower SO_2 to NO_x emission ratio (~0.5). In the future, rapidly motorizing cities in China and the Indian Subcontinent are expected to see their SO_2 to NO_x emission ratios decrease.

The VOC to NO_x emission ratios (mass based) range from ~10 in Jakarta to ~0.7 in Seoul. The highly motorized cities like Seoul, Tokyo, Singapore and cities in the emerging markets regions in China have a higher VOC to NO_x ratios. Major anthropogenic sources of VOC's include motor vehicle exhaust, use of solvents, and the chemical and petroleum industries. NO_x emission sources, mainly from the combustion of fossil fuels include motor vehicles and electricity generating stations.

Carbonaceous particles (BC and OC) account for a significant fraction of $PM_{2.5}$ in the megacities of Asia. The fractions of carbonaceous particles range from >50% in the South and Southeast Asia to <50% in East Asia. The large fraction of carbonaceous particulates reflects in part the inefficient combustion of fossil- and bio-fuels in South and Southeast Asia (Streets et al., 2003).

The high average CO to VOC emission ratios in the cities of China (~4.7) and the Indian Subcontinent (~2.8) compared to the cities in the rest of East Asia and Southeast Asia (~1.1 and ~0.9 respectively), reflect the diverse energy splits between coal, oil and natural gas.

Annex 7 Bibliography on Source Apportionment

NOTE: The bibliography **in this annex** is more extensive than normal to allow potential adopters of top-down methods to identify individuals in their country or region that may serve as local resources as adoption decisions are made and subsequently as implementation is undertaken.

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Receptor Models–Review and Software

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Annex 8 Training and Capacity Building in Hyderabad, India

Mission to APPCB, Hyderabad took place from November 7 to November 18, 2005.

On November 7, Dr. Alan Gertler, Dr. Collin Green, and Dr. Sarath Guttikunda visited the Indian Institute of Chemical Technology, EPTRI, and Jawaharlal Nehru Technological University, laboratories to assess their current capabilities to conduct source apportionment analysis—especially chemical analysis of the samples collected during the course of next one year. Table A8.1 presents the list of questions covered during the visit.

Only the EPTRI facility was found to have the potential to adequately analyze filter samples as part of any future source apportionment study. On-site equipment capabilities included IC (new instrument, not yet functional), XRF (new instrument, not yet functional), AA, carbon (TC/TOC unit, no experience analyzing air samples), and gravimetric analysis. They had a refrigerator for sample storage but no laboratory information management system of filter conditioning area.

During the period of November 8th and 9th, 2005 Alan Gertler conducted a two-day seminar at the APPCB to provide training on and demonstration of the source apportionment methodologies and familiarize participants with the sampling equipment. Training was attended by the staff from APPCB and local academic institutions. Over the two-day period he covered the following topics: aerosol measurement methods, chemical analysis methods, network design, QA and data validation, MiniVol™ sampler operation and maintenance, filter pack assembly, principles of receptor modeling, and application of the chemical mass balance receptor model. Material from this workshop is available for reference. Some of this material is presented in Annex 1.

Following a discussion on 11/9 with APPCB personnel to review previous meteorological and air quality data, we chose a number of potential field monitoring locations. Site visits were then carried out on 11/10 to evaluate suitability for the source attribution study. Sites

Table A8.1 Survey Questions for Chemical Analysis

Questions
What are the analytical capabilities of the lab—Gravimetric, Elemental, Carbon, Ions?
Number of equipments, operating procedures, and qualifications of operator?
What does the sample analysis (samples/day or week?) portfolio/volume currently look like?
Describe labs Data Management System (e.g., LIMS, etc)?
What are the shipping and receiving facilities at the lab?
Do you have a QA/QC program?
What kinds of filter extraction, handling, and storage facilities are available?
List of similar projects participated in the last 3 years?

Source: Integrated Environmental Strategies Program (2007).

visited included Abids, Chikkadpally, Paradise, HCU, Jubilee Hills, KBRN, Punjagutta, and Sainikpuri. The decision was made to use HCU (background), Chikkadpally (residential exposure), and Punjakutta (mobile source dominated).

DRI assisted the APPCB with the purchase of 12 MiniVol™ samplers from Airmetrics, Inc. The sites were installed on 11/11. Sampling then commenced at 0000 on 11/12. Staff at APPCB, Dr. Prasad Dasari, was trained in the sampler operation, filter extraction and storage, and data entry. He was responsible for the day to day operation of samplers. Filter impactors were cleaned in the APPCB laboratory and loaded with the next set of filters.

Annex 9 PM_{10} Emission Estimates Utilizing Bottom-up Analysis

Table A9.1 Reported PM_{10} Emission Estimates for Urban Centers (Bottom-up Analysis)

City, Country	Base Year	Emissions (ktons/yr)	Source
Sao Paulo, Brazil	2002	66.0	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	21.0	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	Review of AQ in Ulaanbaatar, The World Bank (2006)
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	150.0	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

Source: Authors' calculations.

List of Formal Reports

Region/Country	Activity/Report Title	Date	Number
	SUB-SAHARAN AFRICA (AFR)		
Africa Regional	Anglophone Africa Household Energy Workshop (English)	07/88	085/88
	Regional Power Seminar on Reducing Electric Power System Losses in Africa (English)	08/88	087/88
	Institutional Evaluation of EGL (English)	02/89	098/89
	Biomass Mapping Regional Workshops (English)	05/89	—
	Francophone Household Energy Workshop (French)	08/89	—
	Interafrican Electrical Engineering College: Proposals for Short- and Long-Term Development (English)	03/90	112/90
	Biomass Assessment and Mapping (English)	03/90	—
	Symposium on Power Sector Reform and Efficiency Improvement in Sub-Saharan Africa (English)	06/96	182/96
	Commercialization of Marginal Gas Fields (English)	12/97	201/97
	Commercializing Natural Gas: Lessons from the Seminar in Nairobi for Sub-Saharan Africa and Beyond	01/00	225/00
	Africa Gas Initiative—Main Report: Volume I	02/01	240/01
	First World Bank Workshop on the Petroleum Products Sector in Sub-Saharan Africa	09/01	245/01
	Ministerial Workshop on Women in Energy and Poverty Reduction: Proceedings from a Multi-Sector and Multi-Stakeholder Workshop Addis Ababa, Ethiopia, October 23-25, 2002	10/01 03/03	250/01 266/03
	Opportunities for Power Trade in the Nile Basin: Final Scoping Study	01/04	277/04
	Energies modernes et réduction de la pauvreté: Un atelier multi-sectoriel. Actes de l'atelier régional. Dakar, Sénégal, du 4 au 6 février 2003 (French Only)	01/04	278/04
	Énergies modernes et réduction de la pauvreté: Un atelier multi-sectoriel. Actes de l'atelier régional. Douala, Cameroun du 16-18 juillet 2003. (French Only)	09/04	286/04

	Energy and Poverty Reduction: Proceedings from the Global Village Energy Partnership (GVEP) Workshops held in Africa	01/05	298/05
	Power Sector Reform in Africa: Assessing the Impact on Poor People	08/05	306/05
	The Vulnerability of African Countries to Oil Price Shocks: Major Factors and Policy Options. The Case of Oil Importing Countries	08/05	308/05
	Maximizing the Productive Uses of Electricity to Increase the Impact of Rural Electrification Programs	03/08	332/08
Angola	Energy Assessment (English and Portuguese)	05/89	4708-ANG
	Power Rehabilitation and Technical Assistance (English)	10/91	142/91
	Africa Gas Initiative—Angola: Volume II	02/01	240/01
Benin	Energy Assessment (English and French)	06/85	5222-BEN
Botswana	Energy Assessment (English)	09/84	4998-BT
	Pump Electrification Prefeasibility Study (English)	01/86	047/86
	Review of Electricity Service Connection Policy (English)	07/87	071/87
	Tuli Block Farms Electrification Study (English)	07/87	072/87
	Household Energy Issues Study (English)	02/88	—
	Urban Household Energy Strategy Study (English)	05/91	132/91
Burkina Faso	Energy Assessment (English and French)	01/86	5730-BUR
	Technical Assistance Program (English)	03/86	052/86
	Urban Household Energy Strategy Study (English and French)	06/91	134/91
Burundi	Energy Assessment (English)	06/82	3778-BU
	Petroleum Supply Management (English)	01/84	012/84
	Status Report (English and French)	02/84	011/84
	Presentation of Energy Projects for the Fourth Five Year Plan (1983-1987) (English and French)	05/85	036/85
	Improved Charcoal Cookstove Strategy (English and French)	09/85	042/85
	Peat Utilization Project (English)	11/85	046/85
	Energy Assessment (English and French)	01/92	9215-BU
Cameroon	Africa Gas Initiative—Cameroon: Volume III	02/01	240/01
Cape Verde	Energy Assessment (English and Portuguese)	08/84	5073-CV
	Household Energy Strategy Study (English)	02/90	110/90
Central African Republic	Energy Assessment (French)	08/92	9898-CAR
Chad	Elements of Strategy for Urban Household Energy The Case of N'djamena (French)	12/93	160/94
Comoros	Energy Assessment (English and French)	01/88	7104-COM
	In Search of Better Ways to Develop Solar Markets: The Case of Comoros	05/00	230/00

Congo	Energy Assessment (English)	01/88	6420-COB
	Power Development Plan (English and French)	03/90	106/90
	Africa Gas Initiative—Congo: Volume IV	02/01	240/01
Côte d'Ivoire	Energy Assessment (English and French)	04/85	5250-IVC
	Improved Biomass Utilization (English and French)	04/87	069/87
	Power System Efficiency Study (English)	12/87	
	Power Sector Efficiency Study (French)	02/92	140/91
	Project of Energy Efficiency in Buildings (English)	09/95	175/95
	Africa Gas Initiative—Côte d'Ivoire: Volume V	02/01	240/01
Ethiopia	Energy Assessment (English)	07/84	4741-ET
	Power System Efficiency Study (English)	10/85	045/85
	Agricultural Residue Briquetting Pilot Project (English)	12/86	062/86
	Bagasse Study (English)	12/86	063/86
	Cooking Efficiency Project (English)	12/87	
	Energy Assessment (English)	02/96	179/96
Gabon	Energy Assessment (English)	07/88	6915-GA
	Africa Gas Initiative—Gabon: Volume VI	02/01	240/01
The Gambia	Energy Assessment (English)	11/83	4743-GM
	Solar Water Heating Retrofit Project (English)	02/85	030/85
	Solar Photovoltaic Applications (English)	03/85	032/85
	Petroleum Supply Management Assistance (English)	04/85	035/85
Ghana	Energy Assessment (English)	11/86	6234-GH
	Energy Rationalization in the Industrial Sector (English)	06/88	084/88
	Sawmill Residues Utilization Study (English)	11/88	074/87
	Industrial Energy Efficiency (English)	11/92	148/92
	Corporatization of Distribution Concessions through Capitalization	12/03	272/03
Guinea	Energy Assessment (English)	11/86	6137-GUI
	Household Energy Strategy (English and French)	01/94	163/94
Guinea Bissau	Energy Assessment (English and Portuguese)	08/84	5083-GUB
	Recommended Technical Assistance Projects (English & Portuguese)	04/85	033/85
	Management Options for the Electric Power and Water Supply Subsectors (English)	02/90	100/90
	Power and Water Institutional Restructuring (French)	04/91	118/91
Kenya	Energy Assessment (English)	05/82	3800 KE
	Power System Efficiency Study (English)	03/84	014/84

Kenya	Status Report (English)	05/84	016/84
	Coal Conversion Action Plan (English)	02/87	—
	Solar Water Heating Study (English)	02/87	066/87
	Peri-Urban Woodfuel Development (English)	10/87	076/87
	Power Master Plan (English)	11/87	—
	Power Loss Reduction Study (English)	09/96	186/96
	Implementation Manual: Financing Mechanisms for Solar Electric Equipment	07/00	231/00
Lesotho	Energy Assessment (English)	01/84	4676-LSO
Liberia	Energy Assessment (English)	12/84	5279-LBR
	Recommended Technical Assistance Projects (English)	06/85	038/85
	Power System Efficiency Study (English)	12/87	081/87
Madagascar	Energy Assessment (English)	01/87	5700-
	Power System Efficiency Study (English and French)	12/87	075/87
	Environmental Impact of Woodfuels (French)	10/95	176/95
Malawi	Energy Assessment (English)	08/82	3903-
	Technical Assistance to Improve the Efficiency of Fuelwood Use in the Tobacco Industry (English)	11/83	009/83
	Status Report (English)	01/84	013/84
Mali	Energy Assessment (English and French)	11/91	8423-MLI
	Household Energy Strategy (English and French)	03/92	147/92
Islamic Republic of Mauritania	Energy Assessment (English and French)	04/85	5224-
	Household Energy Strategy Study (English and French)	07/90	123/90
Mauritius	Energy Assessment (English)	12/81	3510-
	Status Report (English)	10/83	008/83
	Power System Efficiency Audit (English)	05/87	070/87
	Bagasse Power Potential (English)	10/87	077/87
	Energy Sector Review (English)	12/94	3643-
Mozambique	Energy Assessment (English)	01/87	6128-
	Household Electricity Utilization Study (English)	03/90	113/90
	Electricity Tariffs Study (English)	06/96	181/96
	Sample Survey of Low Voltage Electricity Customers	06/97	195/97
Namibia	Energy Assessment (English)	03/93	11320-
Niger	Energy Assessment (French)	05/84	4642-NIR
	Status Report (English and French)	02/86	051/86

	Improved Stoves Project (English and French)	12/87	080/87
	Household Energy Conservation and Substitution (English and French)	01/88	082/88
Nigeria	Energy Assessment (English)	08/83	4440-UNI
	Energy Assessment (English)	07/93	11672-
	Strategic Gas Plan	02/04	279/04
Rwanda	Energy Assessment (English)	06/82	3779-RW
	Status Report (English and French)	05/84	017/84
	Improved Charcoal Cookstove Strategy (English and French)	08/86	059/86
	Improved Charcoal Production Techniques (English and French)	02/87	065/87
	Energy Assessment (English and French)	07/91	8017-RW
	Commercialization of Improved Charcoal Stoves and Carbonization Techniques Mid-Term Progress Report (English and French)	12/91	141/91
SADC	SADC Regional Power Interconnection Study, Vols. I-IV (English)	12/93	—
SADCC	SADCC Regional Sector: Regional Capacity-Building Program for Energy Surveys and Policy Analysis (English)	11/91	—
Sao Tome and Principe	Energy Assessment (English)	10/85	5803-STP
Senegal	Energy Assessment (English)	07/83	4182-SE
	Status Report (English and French)	10/84	025/84
	Industrial Energy Conservation Study (English)	05/85	037/85
	Preparatory Assistance for Donor Meeting (English and French)	04/86	056/86
	Urban Household Energy Strategy (English)	02/89	096/89
	Industrial Energy Conservation Program (English)	05/94	165/94
Seychelles	Energy Assessment (English)	01/84	4693-SEY
	Electric Power System Efficiency Study (English)	08/84	021/84
Sierra Leone	Energy Assessment (English)	10/87	6597-SL
Somalia	Energy Assessment (English)	12/85	5796-SO
Republic of South Africa	Options for the Structure and Regulation of Natural Gas Industry (English)	05/95	172/95
Sudan	Management Assistance to the Ministry of Energy and Mining	05/83	003/83
	Energy Assessment (English)	07/83	4511-SU
	Power System Efficiency Study (English)	06/84	018/84
	Status Report (English)	11/84	026/84
	Wood Energy/Forestry Feasibility (English)	07/87	073/87

Swaziland	Energy Assessment (English)	02/87	6262-SW
	Household Energy Strategy Study	10/97	198/97
Tanzania	Energy Assessment (English)	11/84	4969-TA
	Peri-Urban Woodfuels Feasibility Study (English)	08/88	086/88
	Tobacco Curing Efficiency Study (English)	05/89	102/89
	Remote Sensing and Mapping of Woodlands (English)	06/90	—
	Industrial Energy Efficiency Technical Assistance (English)	08/90	122/90
	Power Loss Reduction Volume 1: Transmission and Distribution System Technical Loss Reduction and Network Development (English)	06/98	204A/98
	Power Loss Reduction Volume 2: Reduction of Non-Technical Losses (English)	06/98	204B/98
Togo	Energy Assessment (English)	06/85	5221-TO
	Wood Recovery in the Nangbeto Lake (English and French)	04/86	055/86
	Power Efficiency Improvement (English and French)	12/87	078/87
Uganda	Energy Assessment (English)	07/83	4453-UG
	Status Report (English)	08/84	020/84
	Institutional Review of the Energy Sector (English)	01/85	029/85
	Energy Efficiency in Tobacco Curing Industry (English)	02/86	049/86
	Fuelwood/Forestry Feasibility Study (English)	03/86	053/86
	Power System Efficiency Study (English)	12/88	092/88
	Energy Efficiency Improvement in the Brick and Tile Industry (English)	02/89	097/89
	Tobacco Curing Pilot Project (English)	03/89	UNDP Terminal Report
	Energy Assessment (English)	12/96	193/96
	Rural Electrification Strategy Study	09/99	221/99
Zaire	Energy Assessment (English)	05/86	5837-ZR
Zambia	Energy Assessment (English)	01/83	4110-ZA
	Status Report (English)	08/85	039/85
	Energy Sector Institutional Review (English)	11/86	060/86
	Power Subsector Efficiency Study (English)	02/89	093/88
	Energy Strategy Study (English)	02/89	094/88
	Urban Household Energy Strategy Study (English)	08/90	121/90
Zimbabwe	Energy Assessment (English)	06/82	3765-ZIM
	Power System Efficiency Study (English)	06/83	005/83
	Status Report (English)	08/84	019/84

Zimbabwe	Power Sector Management Assistance Project (English)	04/85	034/85
	Power Sector Management Institution Building (English)	09/89	—
	Petroleum Management Assistance (English)	12/89	109/89
	Charcoal Utilization Pre-feasibility Study (English)	06/90	119/90
	Integrated Energy Strategy Evaluation (English)	01/92	8768-ZIM
	Energy Efficiency Technical Assistance Project: Strategic Framework for a National Energy Efficiency Improvement Program (English)	04/94	—
	Capacity Building for the National Energy Efficiency Improvement Programme (NEEIP) (English)	12/94	—
	Rural Electrification Study	03/00	228/00
	Les réformes du secteur de l'électricite en Afrique: Evaluation de leurs conséquences pour les populations pauvres	11/06	306/06
	EAST ASIA AND PACIFIC (EAP)		
Asia Regional	Pacific Household and Rural Energy Seminar (English)	11/90	—
China	County-Level Rural Energy Assessments (English)	05/89	101/89
	Fuelwood Forestry Preinvestment Study (English)	12/89	105/89
	Strategic Options for Power Sector Reform in China (English)	07/93	156/93
	Energy Efficiency and Pollution Control in Township and Village Enterprises (TVE) Industry (English)	11/94	168/94
	Energy for Rural Development in China: An Assessment Based on a Joint Chinese/ESMAP Study in Six Counties (English)	06/96	183/96
	Improving the Technical Efficiency of Decentralized Power Companies	09/99	222/99
	Air Pollution and Acid Rain Control: The Case of Shijiazhuang City and the Changsha Triangle Area	10/03	267/03
	Toward a Sustainable Coal Sector In China	07/04	287/04
	Demand Side Management in a Restructured Industry: How Regulation and Policy Can Deliver Demand-Side Management Benefits to a Growing Economy and a Changing Power System	12/05	314/05
	A Strategy for CBM and CMM Development and Utilization in China	07/07	326/07
	Development of National Heat Pricing and Billing Policy	03/08	330/08
Fiji	Energy Assessment (English)	06/83	4462-FIJ
Indonesia	Energy Assessment (English)	11/81	3543-IND
	Status Report (English)	09/84	022/84
	Power Generation Efficiency Study (English)	02/86	050/86
	Energy Efficiency in the Brick, Tile and Lime Industries (English)	04/87	067/87

Indonesia	Diesel Generating Plant Efficiency Study (English)	12/88	095/88
	Urban Household Energy Strategy Study (English)	02/90	107/90
	Biomass Gasifier Preinvestment Study Vols. I & II (English)	12/90	124/90
	Prospects for Biomass Power Generation with Emphasis on Palm Oil, Sugar, Rubberwood and Plywood Residues (English)	11/94	167/94
Lao PDR	Urban Electricity Demand Assessment Study (English)	03/93	154/93
	Institutional Development for Off-Grid Electrification	06/99	215/99
Malaysia	Sabah Power System Efficiency Study (English)	03/87	068/87
	Gas Utilization Study (English)	09/91	9645-MA
Mongolia	Energy Efficiency in the Electricity and District Heating Sectors	10/01	247/01
	Improved Space Heating Stoves for Ulaanbaatar	03/02	254/02
	Impact of Improved Stoves on Indoor Air Quality in Ulaanbaatar, Mongolia	11/05	313/05
Myanmar	Energy Assessment (English)	06/85	5416-BA
Papua New Guinea (PNG)	Energy Assessment (English)	06/82	3882-
	Status Report (English)	07/83	006/83
	Institutional Review in the Energy Sector (English)	10/84	023/84
	Power Tariff Study (English)	10/84	024/84
Philippines	Commercial Potential for Power Production from Agricultural Residues (English)	12/93	157/93
	Energy Conservation Study (English)	08/94	—
	Strengthening the Non-Conventional and Rural Energy Development Program in the Philippines: A Policy Framework and Action Plan	08/01	243/01
	Rural Electrification and Development in the Philippines: Measuring the Social and Economic Benefits	05/02	255/02
Solomon Islands	Energy Assessment (English)	06/83	4404-SOL
	Energy Assessment (English)	01/92	979-SOL
South Pacific	Petroleum Transport in the South Pacific (English)	05/86	—
Thailand	Energy Assessment (English)	09/85	5793-TH
	Rural Energy Issues and Options (English)	09/85	044/85
	Accelerated Dissemination of Improved Stoves and Charcoal Kilns (English)	09/87	079/87
	Northeast Region Village Forestry and Woodfuels Preinvestment Study (English)	02/88	083/88
	Impact of Lower Oil Prices (English)	08/88	—
	Coal Development and Utilization Study (English)	10/89	—

	Why Liberalization May Stall in a Mature Power Market: A Review of the Technical and Political Economy Factors that Constrained the Electricity Sector Reform in Thailand 1998–2002	12/03	270/03
	Reducing Emissions from Motorcycles in Bangkok	10/03	275/03
Tonga	Energy Assessment (English)	06/85	5498-
Vanuatu	Energy Assessment (English)	06/85	5577-VA
Vietnam	Rural and Household Energy—Issues and Options (English)	01/94	161/94
	Power Sector Reform and Restructuring in Vietnam: Final Report to the Steering Committee (English and Vietnamese)	09/95	174/95
	Household Energy Technical Assistance: Improved Coal Briquetting and Commercialized Dissemination of Higher Efficiency Biomass and Coal Stoves (English)	01/96	178/96
	Petroleum Fiscal Issues and Policies for Fluctuating Oil Prices In Vietnam	02/01	236/01
	An Overnight Success: Vietnam's Switch to Unleaded Gasoline	08/02	257/02
	The Electricity Law for Vietnam—Status and Policy Issues—The Socialist Republic of Vietnam	08/02	259/02
	Petroleum Sector Technical Assistance for the Revision of the Existing Legal and Regulatory Framework	12/03	269/03
Western Samoa	Energy Assessment (English)	06/85	5497-
	SOUTH ASIA (SAR)		
SAR Regional	Toward Cleaner Urban Air in South Asia: Tackling Transport Pollution, Understanding Sources	03/04	281/04
	Potential and Prospects for Regional Energy Trade in the South Asia Region	08/08	334/08
	Trading Arrangements and Risk Management in International Electricity Trade	09/08	336/08
Bangladesh	Energy Assessment (English)	10/82	3873-BD
	Priority Investment Program (English)	05/83	002/83
	Status Report (English)	04/84	015/84
	Power System Efficiency Study (English)	02/85	031/85
	Small Scale Uses of Gas Pre-feasibility Study (English)	12/88	—
	Reducing Emissions from Baby-Taxis in Dhaka	01/02	253/02
	Improving Indoor Air Quality for Poor Families: A Controlled Experiment in Bangladesh	03/08	335/08
India	Opportunities for Commercialization of Non-conventional Energy Systems (English)	11/88	091/88
	Maharashtra Bagasse Energy Efficiency Project (English)	07/90	120/90

India	Mini-Hydro Development on Irrigation Dams and Canal Drops Vols. I, II and III (English)	07/91	139/91
	WindFarm Pre-Investment Study (English)	12/92	150/92
	Power Sector Reform Seminar (English)	04/94	166/94
	Environmental Issues in the Power Sector (English)	06/98	205/98
	Environmental Issues in the Power Sector: Manual for Environmental Decision Making (English)	06/99	213/99
	Household Energy Strategies for Urban India: The Case of Hyderabad	06/99	214/99
	Greenhouse Gas Mitigation In the Power Sector: Case Studies From India	02/01	237/01
	Energy Strategies for Rural India: Evidence from Six States	08/02	258/02
	Household Energy, Indoor Air Pollution, and Health	11/02	261/02
	Access of the Poor to Clean Household Fuels	07/03	263/03
	The Impact of Energy on Women's Lives in Rural India	01/04	276/04
	Environmental Issues in the Power Sector: Long-Term Impacts and Policy Options for Rajasthan	10/04	292/04
	Environmental Issues in the Power Sector: Long-Term Impacts and Policy Options for Karnataka	10/04	293/04
Nepal	Energy Assessment (English)	08/83	4474-NEP
	Status Report (English)	01/85	028/84
	Energy Efficiency & Fuel Substitution in Industries (English)	06/93	158/93
Pakistan	Household Energy Assessment (English)	05/88	—
	Assessment of Photovoltaic Programs, Applications, and Markets (English)	10/89	103/89
	National Household Energy Survey and Strategy Formulation Study: Project Terminal Report (English)	03/94	—
	Managing the Energy Transition (English)	10/94	—
	Lighting Efficiency Improvement Program Phase 1: Commercial Buildings Five Year Plan (English)	10/94	—
	Clean Fuels	10/01	246/01
	Household Use of Commercial Energy	05/06	320/06
Sri Lanka	Energy Assessment (English)	05/82	3792-CE
	Power System Loss Reduction Study (English)	07/83	007/83
	Status Report (English)	01/84	010/84
	Industrial Energy Conservation Study (English)	03/86	054/86
	Sustainable Transport Options for Sri Lanka: Vol. I	02/03	262/03
	Greenhouse Gas Mitigation Options in the Sri Lanka Power Sector: Vol. II	02/03	262/03

Sri Lanka	Sri Lanka Electric Power Technology Assessment (SLEPTA): Vol. III	02/03	262/03
	Energy and Poverty Reduction: Proceedings from South Asia Practitioners Workshop How Can Modern Energy Services Contribute to Poverty Reduction? Colombo, Sri Lanka, June 2–4, 2003	11/03	268/03
	EUROPE AND CENTRAL ASIA (ECA)		
Armenia	Development of Heat Strategies for Urban Areas of Low-income Transition Economies. Urban Heating Strategy for the Republic of Armenia. *Including a Summary of a Heating Strategy for the Kyrgyz Republic*	04/04	282/04
Bulgaria	Natural Gas Policies and Issues (English)	10/96	188/96
	Energy Environment Review	10/02	260/02
Central Asia and The Caucasus	Cleaner Transport Fuels in Central Asia and the Caucasus	08/01	242/01
Central and Eastern Europe	Power Sector Reform in Selected Countries	07/97	196/97
	Increasing the Efficiency of Heating Systems in Central and Eastern Europe and the Former Soviet Union (English and Russian)	08/00	234/00
	The Future of Natural Gas in Eastern Europe (English)	08/92	149/92
Kazakhstan	Natural Gas Investment Study, Volumes 1, 2 & 3	12/97	199/97
Kazakhstan & Kyrgyzstan	Opportunities for Renewable Energy Development	11/97	16855-
Poland	Energy Sector Restructuring Program Vols. I–V (English)	01/93	153/93
	Natural Gas Upstream Policy (English and Polish)	08/98	206/98
	Energy Sector Restructuring Program: Establishing the Energy Regulation Authority	10/98	208/98
Portugal	Energy Assessment (English)	04/84	4824-PO
Romania	Natural Gas Development Strategy (English)	12/96	192/96
	Private Sector Participation in Market-Based Energy-Efficiency Financing Schemes: Lessons Learned from Romania and International Experiences.	11/03	274/03
Slovenia	Workshop on Private Participation in the Power Sector (English)	02/99	211/99
Turkey	Energy Assessment (English)	03/83	3877-TU
	Energy and the Environment: Issues and Options Paper	04/00	229/00
	Energy and Environment Review: Synthesis Report	12/03	273/03
	Turkey's Experience with Greenfield Gas Distribution since 2003	03/07	325/05

MIDDLE EAST AND NORTH AFRICA (MNA)			
Arab Republic of Egypt	Energy Assessment (English)	10/96	189/96
	Energy Assessment (English and French)	03/84	4157-
	Status Report (English and French)	01/86	048/86
Morocco	Energy Sector Institutional Development Study (English and French)	07/95	173/95
	Natural Gas Pricing Study (French)	10/98	209/98
	Gas Development Plan Phase II (French)	02/99	210/99
Syria	Energy Assessment (English)	05/86	5822-SYR
	Electric Power Efficiency Study (English)	09/88	089/88
	Energy Efficiency Improvement in the Cement Sector (English)	04/89	099/89
	Energy Efficiency Improvement in the Fertilizer Sector (English)	06/90	115/90
Tunisia	Fuel Substitution (English and French)	03/90	—
	Power Efficiency Study (English and French)	02/92	136/91
	Energy Management Strategy in the Residential and Tertiary Sectors (English)	04/92	146/92
	Renewable Energy Strategy Study, Volume I (French)	11/96	190A/96
	Renewable Energy Strategy Study, Volume II (French)	11/96	190B/96
	Rural Electrification in Tunisia: National Commitment, Efficient Implementation and Sound Finances	08/05	307/05
Yemen	Energy Assessment (English)	12/84	4892-YAR
	Energy Investment Priorities (English)	02/87	6376-YAR
	Household Energy Strategy Study Phase I (English)	03/91	126/91
	Household Energy Supply and Use in Yemen. Volume I: Main Report and Volume II: Annexes	12/05	315/05
LATIN AMERICA AND THE CARIBBEAN REGION (LCR)			
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