

MEASUREMENTS AND SOURCES OF PM_{2.5}, PM₁₀, AND VOLATILE ORGANIC COMPOUNDS IN GREATER CAIRO

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ABSTRACT

Cairo, Egypt is generally classified as one of the world's "megacities", with an estimated population in excess of 20 million people in the greater Cairo/Giza area. It also suffers from high ambient concentrations of atmospheric pollutants. In order to reduce ambient pollution, the U.S. Agency for International Development (USAID) and the Egyptian Environmental Affairs Agency (EEAA) have supported the Cairo Air Improvement Project (CAIP).

One of the CAIP initiatives was a source attribution study (SAS) to determine contributions from various sources to the observed pollutant levels. As part of the SAS, intensive monitoring studies were carried out during the periods of February/March and October/November 1999 and June 2002. PM₁₀, PM_{2.5}, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) were measured on a 24-hour basis at sites representing background levels, mobile source impacts, industrial impacts, and residential exposure. Major contributors to PM₁₀ 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. The major contributors to VOCs at all sites were mobile emissions, and industrial emissions. Based on these observations, recommendations to improve air quality are presented.

INTRODUCTION

Cairo, Egypt suffers from high ambient concentrations of atmospheric pollutants [1, 2], including particulates (PM), carbon monoxide (CO), oxides of nitrogen (NO_x), ozone (O₃), and sulfur dioxide (SO₂). Nasralla [1] reported particulate lead concentrations that ranged from 0.5 µg/m³ in a residential area to 3.0 µg/m³ at the city center. Sturchio et al. [2] measured total suspended particulate (TSP) and lead concentrations using stable isotopic ratios (²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb) at eleven sites in Cairo. Lead and TSP concentrations ranged from 0.08 µg/m³ and 25 µg/m³ respectively at Helwan to over 3 µg/m³ and 1100 µg/m³ respectively at the city center.

Rodes et al. [3] measured fine (PM_{2.5}) and coarse (PM₁₀-PM_{2.5}) concentrations as a part of a source apportionment study in Cairo from December 1994 through November 1995. The annual average PM₁₀ concentrations exceeded the 24-hour average U.S. standard of 150 µg/m³ at all sites except Ma'adi and the background site. An attempt was made to attribute the high PM levels to specific sources using the Chemical Mass Balance (CMB) source apportionment model. PM₁₀ mass was dominated by the coarse fraction, suggesting a strong influence of fugitive dust sources. Emissions from mobile sources, oil combustion, and open/trash burning dominated the PM_{2.5} apportionments.

In order to develop and implement a pollution-control strategy and to reduce the health impact of air pollution in Cairo the Cairo Air Improvement Project (CAIP) was established. As part of the CAIP, source attribution studies were performed to assess the impact of various sources (e.g., lead smelters, motor vehicles, oil combustion, open burning, geological material, etc.) to ambient pollutant levels. In this paper we report updated PM and VOC source attribution results of ambient monitoring studies performed during the periods of February 21 to March 3, 1999 and October 27 to November 27, 1999 [4], and an additional PM study performed June 8 to June 26, 2002.

EXPERIMENTAL METHODS

Sampling Sites

For the 1999 studies, six sites were selected from CAIP network [4], while two additional sites were monitored in 2002. In order to evaluate inter-site changes over this period, we will only discuss the results from the six sites where measurements were performed in both 1999 and 2002. The six sites included:

Background/Upwind: Kaha, a Nile delta site with significant agricultural activity. During most of the year, the prevailing winds come from this direction.

Industrial/Residential: Shobra El-Khaima and El Massara were chosen to represent residential areas that exhibit potential industrial activities. The Shobra site is located in a heavily industrialized area and is downwind from numerous Pb smelters and other industrial sources. This is one of the most highly polluted areas in the city. The El Massara site is near a number of cement plants and other industrial sources.

Traffic: El Qualaly Square, a site located downtown. The site is close to the road and has high light- and heavy-duty (bus) traffic.

Residential: Helwan and El-Zamalek were chosen. Helwan is impacted by emissions from nearby cement plants and has higher PM levels than some of the other residential areas. El-Zamalek is located on one of the islands in the Nile and represents a residential area with limited nearby sources.

Ambient Measurements

Ambient PM_{2.5} and PM₁₀ samples were collected using the sampling protocol described by Watson et al. [5]. All samples were of 24-hour duration. During the February/March, 1999 study, samples were collected daily, while in the October/November, 1999 and June, 2002 studies samples were collected every other day. Samplers designed to collect samples for chemical analyses were utilized. In addition, we sampled for polycyclic aromatic hydrocarbons (PAHs). The PAHs were critical to apportion the carbon components of the PM based on the uniqueness of PAH compounds associated with motor vehicles and other combustion sources [6]. PAH samples were collected on Teflon-impregnated glass fiber filters followed by an adsorbent cartridge of polyurethane foam and XAD-4 resin (TIGF/PUF/XAD-4).

For the VOC phase of the study, whole air samples, analyzed for C₂-C₁₂ volatile hydrocarbons (VOC's), were collected with 6-liter stainless steel canisters following the

protocol described by Zielinska et al. [7]. Briefly: a stainless steel pump draws in ambient air from the sampling manifold to fill and pressurize the sample canisters. A flow control device maintains a constant flow into the canisters over the desired sample period.

Source Measurements

Source emissions samples were collected using methods similar to those used in the ambient sampling program. In addition, bulk soil and road dust samples were collected 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.

Analytical Methods

Teflon-membrane filters were weighed on an electro-microbalance before and after sampling to determine mass concentrations. Chemical analyses were performed on Teflon-membrane and quartz-fiber filters following the methodology described by Watson and Chow [8]. Briefly, the Teflon-membrane filters are analyzed for elements (Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Rb, Sr, Ba, U and Pb) by x-ray fluorescence (XRF). One-half of the quartz filter is extracted with distilled-deionized water and the extract was analyzed for chloride, nitrate, and sulfate ions by ion chromatography (IC), for ammonium by automated colorimetry (AC), and for sodium and potassium by atomic absorption (AA). Organic and elemental carbon are measured by thermal/optical reflectance (TOR) on 0.5 cm² punches taken from the remaining half of the quartz-fiber filter [9]. The PAHs samples were analyzed following the protocol described by Fujita et al. [6]. For the VOC samples, the canisters are shipped back to the laboratory and analyzed for C₂-C₁₂ hydrocarbons using gas chromatography with a flame ionization detector (GC/FID), which is the established technique for monitoring ozone precursors in ambient air.

Receptor Modeling Methods

The Chemical Mass Balance (CMB) receptor model was used to apportion PM and its chemical constituents to their sources [10]. The CMB procedure requires several steps. First, the contributing sources must be identified and their chemical profiles must be entered. Then the chemical species to be included in the model must be selected. The next step is the estimation of the fractions of each chemical species contained in each source type and the estimation of the uncertainties in both the ambient concentrations and source contributions. The final step is the solution of the set of chemical mass balance equations. These procedures are described in detail in an application and validation protocol [11].

RESULTS

Mass and Inorganic Chemical Species

Mass concentrations in both size fractions (Table 1, measured mass column) were higher at all sites (except for PM_{2.5} at Shobra) during the fall 1999 sampling period [4]. Shobra exhibited the highest average PM₁₀ and PM_{2.5} mass concentrations. The lowest values in both size fractions were observed at Helwan, a residential location. The background/upwind site, Kaha, generally had the second lowest mass levels. The correlations between measured

and reconstructed (sum of species) were very high, which indicates that the data quality for the particulate measurements was quite good. The sum of the species consistently accounted for 70-80% of the measured mass. The difference is accounted for by the fact that the sum of species does not contain oxygen associated with geological species (e.g., Al, Fe, Si) or hydrogen, oxygen, nitrogen, and sulfur associated with organic carbon.

The $PM_{2.5}/PM_{10}$ ratio varied from 0.3 at El Massara to 0.8 at Shobra. El Massara is an industrial/residential location impacted by emissions from nearby cement plants. The ratio of 0.3 at El Massara is consistent with coarse particle emissions from those activities. Shobra is a highly industrialized site with a number of lead smelters in the vicinity. The ratio of 0.8 is likely due to the impact of fresh combustion emissions, although it is still unusually high. One might have also expected very high ratios at El Qualaly, the mobile source site; however, the observed ratio was 0.4. This site also had high levels of crustal species in the PM_{10} fraction, likely due to resuspended road dust, leading to the reduced ratio.

A detailed discussion of the results of the chemical analysis of the 1999 samples is contained in Lowenthal et al. [12]. Crustal components (Si, Ca, Fe, and Al) were significant at all sites. The majority of crustal material was in the coarse (PM_{10} - $PM_{2.5}$) fraction. The highest concentrations of PM_{10} crustal species were found at Shobra and El Massara, probably as a result of fugitive dust emissions from industrial operations at these sites. Organic carbon (OC), and elemental carbon (EC) were major components of PM at all sites. Potential sources include mobile emissions, open burning, and fossil fuel combustion. The highest average PM_{10} OC levels were observed at El Qualaly and Shobra.

Shobra exhibited the highest lead (Pb) concentrations. The average PM_{10} and $PM_{2.5}$ ambient lead concentrations were 7-34 and 5-27 $\mu\text{g}/\text{m}^3$, respectively. Note that average winter 1999 Pb concentrations at Shobra were five times higher than those in summer 2002. Because other mass and species concentrations were generally higher during 1999, we suspect that industrial lead operations may have been shut down or diminished at Shobra prior to the summer 2002 period. Lead concentrations at Shobra and Cairo in general are in excess of PM_{10} and $PM_{2.5}$ mass concentrations observed in many cities in the world. It should be noted that leaded fuel was phased out in 1996 and so most of this Pb comes from other sources such as smelters and contaminated soil.

Organic Chemical Species

Fall VOC concentrations were generally higher than those observed in winter. The highest average VOC concentrations were found at El Qualaly during both fall (2037 ± 1369 ppb) and winter (1849 ± 298 ppb). This is consistent with the high volume of mobile source emissions expected at this site. The next highest VOC concentrations were found at Al Zamalek (winter VOC = 1282 ± 965 ppb; fall VOC = 879 ± 213 ppb) and at Shobra (fall VOC = 1149 ± 822 ppb; winter VOC = 914 ± 171 ppb). The lowest VOC concentrations were found at El Massara, Helwan, and Kaha.

The temporal variations of VOC were consistent and largely invariant among the six sites during winter. All sites seemed to experience a minimum in VOC concentrations at the end of February, 1999. During fall, all sites experienced VOC maxima on November 22, 1999 and elevated concentrations on the two days leading up to it. Again, the lowest concentrations in fall were found at El Massara, Helwan, and Kaha.

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

PM Source Attribution Results

The PM source attribution results are presented in Table 1. The CMB model diagnostics for PM are quite good. For all average PM samples R² was between 0.94 and 1.00. R² greater than 0.8 is considered acceptable [11]. The calculated mass was within 10% of the measured mass. Chi-square, another measure of the goodness of fit, varied from 0.19 to 1.59, with the lowest values indicating the best fit. A chi-square less than 2 is considered acceptable [11]. A summary, by site, of the CMB results is presented below:

Al Zamalek: The major sources of PM₁₀ were geological material, Mazut oil, mobile sources, and open burning. Most of the secondary sulfate, ammonium chloride, and combustion (motor vehicle, open burning, and oil) were in the fine fraction. Lead and copper smelter contributions were small at this site.

El Qualaly : This site was dominated by mobile source emissions. PM₁₀ was dominated by geological, mobile source, and open burning. About half of the mobile and open burning emissions were in the PM_{2.5} fraction. The lead and copper smelter contributions to PM₁₀ were significant at this site

Helwan: PM₁₀ at this site was dominated by geological material. While the marine contribution was almost entirely in the coarse (PM₁₀-PM_{2.5}) fraction, mobile, Mazut, and open burning contributions at this site were almost entirely in the fine fraction. Copper smelter contributions were detected at low levels (1-2%) in both size fractions.

Kaha: The largest contributors to PM₁₀ were open burning and geological dust. Mobile source and Mazut oil contributions were small compared with other sites. PM_{2.5} was dominated by open burning.

El Massara: The PM₁₀ fraction was dominated by geological material, cement, mobile sources, and open burning. The fine fraction was dominated by open burning and mobile emissions. The lead and copper smelter contributions were found almost entirely in the fine fraction.

Shobra: The most unusual aspect of this location is the high PM Pb levels. Eighty percent of the lead contribution was in the PM_{2.5} fraction. Most of this Pb is in the form of fresh emissions from secondary Pb smelters in the vicinity. Contributors to PM₁₀ included geological material and mobile source emissions. The PM_{2.5} apportionment shows a similar distribution of source contributions, which is consistent with dominance of fine particles at this site.

Location	Year	Size	Measured Mass	Predicted Mass	Geological Material	Lead Smelters	Copper Smelters	Steel Industry	Heavy Oil	Motor Vehicles	Open Burning	Marine	Ammonium Sulfate	Ammonium Nitrate	Ammonium Chloride	Cement Plants
El Massara	Winter 1999	PM10	186 ± 9	187 ± 18	65 ± 6	1 ± 0	1 ± 0	1 ± 1	2 ± 0	12 ± 3	44 ± 4	11 ± 1	3 ± 7	0 ± 0	3 ± 0	44 ± 14
El Massara	Winter 1999	PM2.5	61 ± 3	67 ± 3	7 ± 1	1 ± 0	0 ± 0	1 ± 0	3 ± 0	13 ± 2	19 ± 2	2 ± 0	4 ± 1	3 ± 0	5 ± 1	7 ± 1
El Massara	Fall 1999	PM10	317 ± 17	348 ± 33	145 ± 15	0 ± 0	1 ± 0	4 ± 1	1 ± 0	11 ± 3	103 ± 9	5 ± 1	13 ± 5	13 ± 2	16 ± 13	36 ± 23
El Massara	Fall 1999	PM2.5	107 ± 6	116 ± 6	12 ± 1	0 ± 0	1 ± 0	2 ± 0	4 ± 1	12 ± 2	48 ± 5	0 ± 0	9 ± 1	5 ± 1	17 ± 1	5 ± 1
El Massara	Summer 2002	PM10	175 ± 9	202 ± 17	86 ± 8	0 ± 0	0 ± 0	1 ± 1	1 ± 0	8 ± 2	54 ± 5	6 ± 1	8 ± 2	8 ± 1	0 ± 0	29 ± 15
El Massara	Summer 2002	PM2.5	48 ± 3	61 ± 3	6 ± 1	0 ± 0	0 ± 0	0 ± 0	1 ± 0	14 ± 2	25 ± 2	1 ± 0	8 ± 1	2 ± 0	0 ± 0	3 ± 0
El Qualaly	Winter 1999	PM10	220 ± 11	191 ± 11	77 ± 9	7 ± 1	3 ± 0	5 ± 1	3 ± 0	33 ± 4	34 ± 4	3 ± 1	1 ± 3	6 ± 1	18 ± 2	0 ± 0
El Qualaly	Winter 1999	PM2.5	85 ± 4	72 ± 3	3 ± 0	2 ± 0	2 ± 0	1 ± 0	6 ± 1	21 ± 2	14 ± 1	0 ± 0	5 ± 1	4 ± 0	13 ± 1	0 ± 0
El Qualaly	Fall 1999	PM10	252 ± 13	269 ± 17	70 ± 10	3 ± 0	3 ± 0	4 ± 1	2 ± 0	43 ± 6	104 ± 10	2 ± 1	8 ± 8	11 ± 1	20 ± 2	0 ± 0
El Qualaly	Fall 1999	PM2.5	135 ± 7	149 ± 7	3 ± 1	2 ± 0	3 ± 0	1 ± 0	5 ± 2	46 ± 4	56 ± 5	0 ± 0	9 ± 2	6 ± 1	19 ± 1	0 ± 0
El Qualaly	Summer 2002	PM10	136 ± 7	137 ± 8	68 ± 6	1 ± 0	0 ± 0	2 ± 0	1 ± 0	24 ± 2	25 ± 3	3 ± 1	6 ± 2	6 ± 1	0 ± 0	0 ± 0
El Qualaly	Summer 2002	PM2.5	59 ± 3	56 ± 3	1 ± 0	0 ± 0	0 ± 0	0 ± 0	2 ± 1	29 ± 2	11 ± 1	1 ± 0	9 ± 1	1 ± 0	0 ± 0	0 ± 0
Al Zamalek	Winter 1999	PM10	127 ± 6	112 ± 7	29 ± 4	2 ± 0	1 ± 0	3 ± 0	3 ± 0	16 ± 2	22 ± 2	4 ± 1	1 ± 2	6 ± 1	23 ± 2	3 ± 4
Al Zamalek	Winter 1999	PM2.5	62 ± 3	58 ± 3	1 ± 0	1 ± 0	1 ± 0	1 ± 0	6 ± 0	9 ± 1	12 ± 1	0 ± 0	5 ± 1	3 ± 0	18 ± 1	0 ± 0
Al Zamalek	Fall 1999	PM10	249 ± 13	262 ± 17	80 ± 9	1 ± 0	2 ± 0	5 ± 1	2 ± 0	24 ± 4	108 ± 9	6 ± 1	7 ± 9	11 ± 1	15 ± 4	0 ± 0
Al Zamalek	Fall 1999	PM2.5	132 ± 7	143 ± 7	5 ± 1	1 ± 0	2 ± 0	1 ± 0	5 ± 2	29 ± 4	60 ± 5	1 ± 0	11 ± 2	7 ± 1	20 ± 1	1 ± 0
Al Zamalek	Summer 2002	PM10	99 ± 5	98 ± 7	41 ± 5	0 ± 0	0 ± 0	2 ± 0	1 ± 0	19 ± 3	19 ± 2	4 ± 1	8 ± 2	5 ± 1	0 ± 0	0 ± 0
Al Zamalek	Summer 2002	PM2.5	40 ± 2	39 ± 2	2 ± 0	0 ± 0	0 ± 0	0 ± 0	2 ± 0	14 ± 2	10 ± 1	1 ± 0	9 ± 1	1 ± 0	0 ± 0	0 ± 0
Helwan	Winter 1999	PM10	88 ± 5	85 ± 8	27 ± 4	0 ± 0	1 ± 0	2 ± 0	1 ± 0	13 ± 3	18 ± 2	5 ± 1	2 ± 3	4 ± 0	2 ± 1	11 ± 5
Helwan	Winter 1999	PM2.5	29 ± 2	30 ± 2	1 ± 0	0 ± 0	0 ± 0	0 ± 0	1 ± 0	8 ± 1	10 ± 1	0 ± 0	4 ± 1	2 ± 0	3 ± 0	0 ± 0
Helwan	Fall 1999	PM10	146 ± 9	190 ± 15	78 ± 11	0 ± 0	2 ± 0	3 ± 1	1 ± 0	13 ± 3	63 ± 7	6 ± 5	8 ± 4	7 ± 1	5 ± 1	4 ± 5
Helwan	Fall 1999	PM2.5	100 ± 6	84 ± 5	5 ± 1	0 ± 0	2 ± 0	2 ± 0	2 ± 1	9 ± 2	39 ± 4	1 ± 0	8 ± 1	4 ± 1	10 ± 1	1 ± 0
Helwan	Summer 2002	PM10	142 ± 7	142 ± 9	73 ± 7	0 ± 0	0 ± 0	3 ± 1	0 ± 0	22 ± 3	25 ± 4	5 ± 1	5 ± 2	8 ± 1	0 ± 0	0 ± 0
Helwan	Summer 2002	PM2.5	48 ± 3	54 ± 3	10 ± 1	0 ± 0	0 ± 0	1 ± 0	1 ± 0	15 ± 2	16 ± 2	1 ± 0	6 ± 1	2 ± 0	0 ± 0	0 ± 0
Kaha	Winter 1999	PM10	93 ± 5	97 ± 6	12 ± 3	0 ± 0	0 ± 0	1 ± 0	2 ± 0	13 ± 3	35 ± 3	3 ± 1	2 ± 2	6 ± 1	23 ± 2	0 ± 0
Kaha	Winter 1999	PM2.5	50 ± 3	51 ± 2	0 ± 0	0 ± 0	0 ± 0	0 ± 0	3 ± 0	4 ± 1	19 ± 1	0 ± 0	5 ± 1	4 ± 1	15 ± 1	0 ± 0
Kaha	Fall 1999	PM10	205 ± 11	237 ± 14	52 ± 6	0 ± 0	0 ± 0	1 ± 1	1 ± 0	14 ± 3	123 ± 10	9 ± 4	6 ± 6	11 ± 1	18 ± 2	0 ± 0
Kaha	Fall 1999	PM2.5	111 ± 6	130 ± 8	5 ± 1	0 ± 0	0 ± 0	0 ± 0	3 ± 1	11 ± 3	82 ± 8	0 ± 0	8 ± 1	7 ± 1	14 ± 1	0 ± 0
Kaha	Summer 2002	PM10	100 ± 5	97 ± 5	39 ± 3	0 ± 0	0 ± 0	1 ± 0	1 ± 0	9 ± 1	34 ± 3	4 ± 1	5 ± 2	5 ± 1	0 ± 0	0 ± 0
Kaha	Summer 2002	PM2.5	35 ± 2	33 ± 2	3 ± 0	0 ± 0	0 ± 0	0 ± 0	1 ± 0	9 ± 1	12 ± 1	0 ± 0	7 ± 1	0 ± 0	0 ± 0	0 ± 0
Shobra	Winter 1999	PM10	265 ± 14	219 ± 10	51 ± 5	53 ± 5	10 ± 1	11 ± 1	4 ± 0	21 ± 4	40 ± 5	6 ± 1	0 ± 0	6 ± 1	18 ± 2	0 ± 0
Shobra	Winter 1999	PM2.5	216 ± 11	171 ± 7	36 ± 3	43 ± 4	9 ± 1	14 ± 1	9 ± 3	26 ± 4	5 ± 1	3 ± 1	2 ± 2	5 ± 1	16 ± 1	2 ± 1
Shobra	Fall 1999	PM10	360 ± 19	349 ± 25	90 ± 10	17 ± 3	7 ± 1	14 ± 2	4 ± 0	23 ± 5	147 ± 13	4 ± 7	5 ± 11	12 ± 2	14 ± 2	11 ± 11
Shobra	Fall 1999	PM2.5	174 ± 9	203 ± 11	20 ± 2	12 ± 2	6 ± 1	2 ± 0	9 ± 3	26 ± 5	89 ± 9	0 ± 0	12 ± 2	7 ± 1	20 ± 2	0 ± 0
Shobra	Summer 2002	PM10	154 ± 8	143 ± 7	52 ± 5	11 ± 2	3 ± 0	9 ± 1	3 ± 0	15 ± 2	34 ± 4	5 ± 1	5 ± 2	6 ± 1	0 ± 0	0 ± 0
Shobra	Summer 2002	PM2.5	61 ± 3	60 ± 3	2 ± 0	7 ± 1	2 ± 0	4 ± 0	6 ± 1	13 ± 2	15 ± 2	1 ± 0	10 ± 1	1 ± 0	0 ± 0	0 ± 0

Table 1. Summary of PM_{2.5} and PM₁₀ source attribution results for the six intensive sites (average ± standard deviation, µg/m³).

VOC Source Attribution Results

The CMB results are presented for each winter and fall sample in Table 2. The VOC fits were remarkably good. For winter samples, the percent of total non-methane hydrocarbons (VOC) accounted for, Chi-squared, and R^2 averaged 99.5%, 2.8, and 0.95, respectively. For fall samples, the percent of VOC accounted for, Chi-squared, and R^2 averaged 103.0%, 2.6, and 0.95, respectively.

Site	Date	Predicted	Measured	Evaporative Emissions	Motor Vehicles	Industrial	Compressed Natural Gas
El Massara	Winter	395 ± 24	407 ± 15	27 ± 6	96 ± 10	215 ± 18	57 ± 11
El Massara	Fall	797 ± 63	763 ± 21	80 ± 16	183 ± 26	389 ± 46	145 ± 30
El Qualaly	Winter	1931 ± 103	1849 ± 22	220 ± 45	1008 ± 67	578 ± 58	124 ± 28
El Qualaly	Fall	2242 ± 147	2037 ± 50	371 ± 61	1047 ± 88	639 ± 89	186 ± 46
Al Zamalik	Winter	981 ± 53	879 ± 32	140 ± 23	449 ± 32	304 ± 31	88 ± 17
Al Zamalik	Fall	1399 ± 95	1281 ± 33	267 ± 39	544 ± 52	437 ± 61	150 ± 33
Helwan	Winter	334 ± 19	365 ± 13	19 ± 7	175 ± 12	112 ± 11	28 ± 6
Helwan	Fall	570 ± 36	628 ± 15	88 ± 15	210 ± 20	195 ± 22	77 ± 15
Kaha	Winter	368 ± 22	375 ± 13	16 ± 5	94 ± 9	203 ± 17	56 ± 9
Kaha	Fall	452 ± 33	462 ± 11	32 ± 7	93 ± 12	226 ± 24	100 ± 18
Shobra	Winter	833 ± 47	914 ± 14	62 ± 15	304 ± 25	375 ± 33	93 ± 17
Shobra	Fall	1258 ± 121	1149 ± 29	162 ± 28	361 ± 44	534 ± 89	201 ± 64

Table 2. Summary of VOC source attribution results at the six intensive sites during the winter and fall, 1999 (average ± standard deviation, ppb).

The VOC apportionments were also consistent spatially and temporally. On-road mobile and industrial (e.g., lead smelter/LPG) emissions dominated contributions to VOC at all sites during both seasons. Further, evaporative emission contributions were relatively higher during the fall season. This may be related to the observation that average temperatures were about 5 °C higher during the fall season. The results for the six sites during both seasons are summarized below. We refer to evaporative emissions, mobile, lead smelter plus liquid petroleum gas, and natural gas contributions as evaporative emissions, motor vehicles, industrial, and compressed natural gas, respectively.

Al Zamalek: Average relative contributions of evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to VOCs were 14.3, 45.8, 31.0, and 9.0%, respectively, in winter, and 19.1, 38.9, 31.3, and 10.7%, respectively in fall. While the absolute contributions varied somewhat from day to day, mainly as a function of VOC concentration, the relative source contributions were quite stable during both seasons. For example, the largest day- to-day variation of any relative (%) source contribution was 36% (coefficient of variation) for the industrial sources during fall.

El Qualaly: The relative source contributions were similar during both seasons. Average relative contributions of evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to NHMC were 11.4, 52.2, 29.9, and 6.4%, respectively, in winter, and 16.5, 46.7, 28.5, and 8.3%, respectively in fall. This site had the highest VOC concentrations during both seasons. Absolute contributions of motor vehicles plus evaporative emissions sources were a factor of two higher at this site, which is dominated by mobile emissions. The temporal variation of the relative source contributions was quite low during both seasons, e.g., 21% for evaporative emissions during winter and 21% for industrial during fall.

Helwan: Average relative contributions of evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to NHMC were 5.8, 52.3, 33.6, and 8.3%, respectively, in winter, and 15.4, 36.9, 34.2, and 13.5%, respectively in fall. The absolute average evaporative emissions and compressed natural gas contributions were 4 and 3 times higher, respectively, in fall. The motor vehicles contribution in fall (210 ppb) was only somewhat higher than the motor vehicles contribution in winter (174 ppb). In relative terms, the temporal variation of the major source contributions was less than 45% during both seasons.

Kaha: Average relative contributions of evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to VOC were 4.3, 25.4, 55.0, and 15.2%, respectively, in winter, and 7.1, 20.6, 50.1, and 22.2%, respectively in fall. The most dramatic seasonal changes in source contributions were for evaporative emissions and compressed natural gas, which increased from 16 to 32 ppb and 56 to 100 ppb from winter to fall. Again, the relative source contributions didn't vary much at this site. Except for evaporative emissions (85% and 44% in fall, and winter, respectively), the temporal variation of the other sources varied by less than 24%. The industrial contributions at this "background" site were 203 and 226 ppb during winter and fall, respectively. In light of the similarity between PM_{2.5} concentrations at Kaha and the other sites (except Shobra), relatively high VOC concentrations and source contributions at Kaha don't appear to be unusual.

El Massara: Average relative source contributions were similar in both seasons. evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to NHMC were 6.9, 24.2, 54.4, and 14.5%, respectively, in winter, and 10.0, 23.0, 48.9, and 18.2%, respectively in fall. While their relative mix was similar, absolute source contributions were about 2 times higher in fall than in winter, following a similar increase in VOC concentrations.

Shobra: Average relative contributions of evaporative emissions, motor vehicles, industrial, and compressed natural gas sources to NHMC were 7.4, 36.4, 45.0, and 11.1%, respectively, in winter, and 12.9, 28.7, 42.4, and 16.0%, respectively in fall. While the evaporative emissions contribution in fall (162 ppb) was nearly 3 times larger than that in winter (62 ppb), differences between fall and winter motor vehicles (362 and 304 ppb, respectively) and industrial (534 and 375 ppb), respectively) were less pronounced.

RECOMMENDATIONS

Many pollutants such as O₃, CO, NO_x, and SO₂ are not routinely measured in the greater Cairo area. Measurements of these species, along with PM are critical if one is to address air quality issues in Cairo. For PM, based on the source attribution results reported in this paper, we find that geological material, open burning, mobile sources, and ammonium nitrate are the major contributors to PM₁₀ and open burning, mobile sources, and ammonium nitrate are the major contributors to PM_{2.5}. The major sources of VOCs are tended to be mobile sources and industrial emissions. In order to continue to improve air quality, contributions from these sources must be reduced. Some of the possible approaches may be easier to implement in the Greater Cairo area than others; however, to reduce ambient concentrations below Egyptian, US, and WHO guidelines, decreases in contributions from all these sources will be required.

General recommendations:

- Perform routine measurements of air pollutants (e.g., CO, SO₂, NO_x, O₃, in addition to PM) in the greater Cairo area in order to determine baseline levels of pollutants and evaluate concentration trends.
- Develop a validated emissions inventory that can be used for regulatory decisions.
- Institute a program to reduce traffic congestion (e.g., a bus-rapid-transit system). This will reduce mobile source emissions and resuspended road dust.
- Implement programs to reduce area source emissions.
- Implement a comprehensive enforcement program to ensure industrial compliance with air quality regulations.
- Develop policies to encourage retrofitting existing industrial sources with lower emitting technologies.
- Involve the public and other stakeholders in the planning and implementation of any improvement strategies.

Specific recommendations:

- Initiate a program to collect garbage and eliminate open burning in both residential and agricultural areas. This will reduce the open burning component of PM.
- Expand and enforce the vehicle emissions and testing program to reduce mobile source emissions. This will also reduce NO_x emissions, which would lead to a reduction in the observed ammonium nitrate component of PM.
- Retrofit diesel buses to reduce PM and NO_x emissions.
- Reduce geological emissions by paving the roads to reduce resuspended road dust and implement control measures at industrial facilities to reduce fugitive emissions from piles of raw materials.

SUMMARY

An intensive PM₁₀, PM_{2.5}, and VOC sampling program was carried out at six sites in the greater Cairo area during a winter period from February 18 to March 4, 1999 and during a fall period from October 29 to November 27, 1999. Additional PM measurements were performed during a summer period from June 8 to June 26, 2002. Medium volume samplers were used to collect PM_{2.5}, PM₁₀, and PAH samples for subsequent chemical analysis and source apportionment modeling. Canister samplers were used to collect VOCs.

The CMB receptor model coupled with source profiles measured during the CAIP and from previous studies was used to estimate source contributions to PM_{2.5} and PM₁₀ mass. Depending on the sites, major contributors to PM₁₀ 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 winter 1999 at Shobra. VOC concentrations were generally higher in fall than in winter. El Qualaly, the site chosen to represent mobile emissions, displayed the highest average VOC concentrations of any site, by factors of 2 or more, in both winter (1849 ppb) and fall (2037 ppb). The major contributors to VOCs at all sites in both seasons were mobile source emissions and industrial emissions. We interpret the latter to represent industrial processes

that may be fueled by LPG. Mobile evaporative emissions contributions were higher in both absolute and relative terms at all sites during the fall season, when average temperatures were about 5° C higher than those in winter.

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