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Environ. Res. Lett. **8** (2013) 044025 (9pp) doi:10.1088/1748-9326/8/4/044025

Chemical composition and sources of particle pollution in affluent and poor neighborhoods of Accra, Ghana

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Received 7 September 2013
Accepted for publication 10 October 2013
Published 30 October 2013
Online at stacks.iop.org/ERL/8/044025

Abstract
The highest levels of air pollution in the world now occur in developing country cities, where air pollution sources differ from high-income countries. We analyzed particulate matter (PM) chemical composition and estimated the contributions of various sources to particle pollution in poor and affluent neighborhoods of Accra, Ghana. Elements from earth's crust were most abundant during the seasonal Harmattan period between late December and late January when Saharan dust is carried to coastal West Africa. During Harmattan, crustal particles accounted for 55 μg m^{-3} (37%) of fine particle ($PM_{2.5}$) mass and 128 μg m^{-3} (42%) of PM_{10} mass. Outside Harmattan, biomass combustion, which was associated with higher black carbon, potassium, and sulfur, accounted for between 10.6 and 21.3 μg m^{-3} of fine particle mass in different neighborhoods, with its contribution largest in the poorest neighborhood. Other sources were sea salt, vehicle emissions, tire and brake wear, road dust, and solid waste burning. Reducing air pollution in African cities requires policies related to energy, transportation and urban planning, and forestry and agriculture, with explicit attention to impacts of each strategy in poor communities. Such cross-sectoral integration requires emphasis on urban environment and urban poverty in the post-2015 Development Agenda.

Keywords: air pollution, particulate matter, source apportionment, urbanization, sustainable development, Africa

S Online supplementary data available from stacks.iop.org/ERL/8/044025/mmedia

1. Introduction

The highest levels of air pollution in the world now occur in cities in Asia, Middle East, and Africa [1]. In these settings, the concentrations of fine particles (less than 2.5 μm in aerodynamic diameter; $PM_{2.5}$), which are associated with hazardous effects on health, approach or reach 100 $\mu g\ m^{-3}$, compared to less than 20 $\mu g\ m^{-3}$ in most European and North American cities [1]. The sources of air pollution in developing country cities include those that are common in high-income nations, e.g., vehicle emissions, as well as biomass and coal combustion for household and commercial purposes and resuspended dust from unpaved roads. In coastal West Africa, sea salt and long-range-transported Saharan dust may also be sources of particles in some seasons [2–4]. Yet little is known about the relative contributions of these sources to pollution levels in African cities, where the urban population is growing faster than any other region; neither is it known how the source diversity affects particle chemistry, which may in turn affect both health hazards and impacts on anthropogenic climate change.

We conducted a study in Accra, Ghana, one of Africa's fastest growing cities to understand the levels, chemical properties, and sources of particle pollution. Three quarters of sub-Saharan Africa's population use biomass fuels as their main source of energy, including over one half of urban households [5, 6]. In Accra, and other developing country cities, there are significant differences in road conditions, traffic patterns, and fuel use between the affluent neighborhoods and poor 'slum' areas [6–8]. For this reason, we collected data at sites located in poor and affluent neighborhoods.

2. Materials and methods

We collected particulate matter (PM) samples between September 2007 and August 2008 in four neighborhoods of varying degrees of poverty and affluence. The four neighborhoods lie on a line from the coast to Accra's northern boundaries: James Town/Usher Town (JT), Asylum Down (AD), Nima (NM) and East Legon (EL) (figure 1). JT and NM are densely populated low-income communities where most residents use biomass for cooking at home and for street food. AD is a middle-class neighborhood and EL is an upper-class, sparsely-populated residential neighborhood where most families live on large plots of land and in modern low-rise homes. Fewer people use biomass fuels in AD and EL than in JT and NM.

Between September 2007 and August 2008, we simultaneously operated five monitoring sites in four neighborhoods (JT, AD, NM-1, NM-2, and EL). Measurements were done for one 48-h period every six days. We also used geo-coded data from the Ghana Population and Housing Census on household socioeconomic status and fuel use and data from the Ghana Survey Department on road locations and types.

PM mass concentrations were measured on a Mettler Toledo MT5 microbalance at the Harvard School of Public Health Laboratory. The elemental concentrations of the samples were quantified by energy dispersive x-ray fluorescence (ED-XRF) at the Institute of Astronomy, Geophysics and Atmospheric Science, University of Sao Paulo, Brazil. Measured elements in our study included sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), nickel (Ni), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), bromine (Br), and lead (Pb). We converted the major crustal elements to their most abundant oxide forms as most of earth's crust consists of mineral oxides. We also converted sulfur (S) to sulfate (SO_4^{2-}), the most common form in the atmosphere. Other elements, whose forms in the atmosphere vary by source, are reported in their elemental form. Gallium (Ga), selenium (Se), rubidium (Rb), yttrium (Y), niobium (Nb), barium (Ba), and hafnium (Hf) were excluded from the analysis because a relatively large number of the measured concentrations were below the limit of detection.

Black carbon (BC) concentrations were estimated primarily using data on reflectance coefficients. For 52 site-days, we also collected co-located PM samples on quartz fiber filters, which were used to directly measure BC concentrations. We used site-days with both direct measurement and data on reflectance coefficient to develop a regression equation that related the natural logarithm (ln) of BC concentration to the reflectance coefficient. The regression equation was then used to estimate the BC concentrations of the remaining samples whose reflectance, but not BC, had been measured. We used the positive matrix factorization (PMF) of the elemental mass to identify and quantify the sources of PM at five sites [9].

Details on methods for particle sample collection, measurement of total and elemental mass concentrations, and the PMF model are described in the supplementary material (available at stacks.iop.org/ERL/8/044025/mmedia).

3. Results

3.1. Particle chemical composition

Particle mass concentrations were reported elsewhere [10]. Here, we analyzed and report the elemental composition of $PM_{2.5}$ and PM_{10}; PM_{10} includes both fine and coarse fractions in the respirable range. Total particle mass, crustal components like SiO_2, and to a lesser extent K peaked sharply in all neighborhoods between December and February (figure 2), the seasonal Harmattan period when northeast trade winds blow from the Sahara at an altitude of about 1500 m, carrying large amounts of Saharan dust and emissions from dry-season bushfires [2–4]. SO_4^{2-} also had a strong seasonal pattern, peaking in January and August and being lowest in May and October. The latter months coincide with rainy seasons, when wet deposition helps remove the water-soluble SO_4^{2-}. In contrast to these components, chlorine concentration changed little over time but had a noticeable spatial pattern, being highest in JT and lowest in EL; JT also had higher sodium (Na) concentrations; see tables 1 and 2. JT is close to the ocean and hence has more particles from sea spray. Black

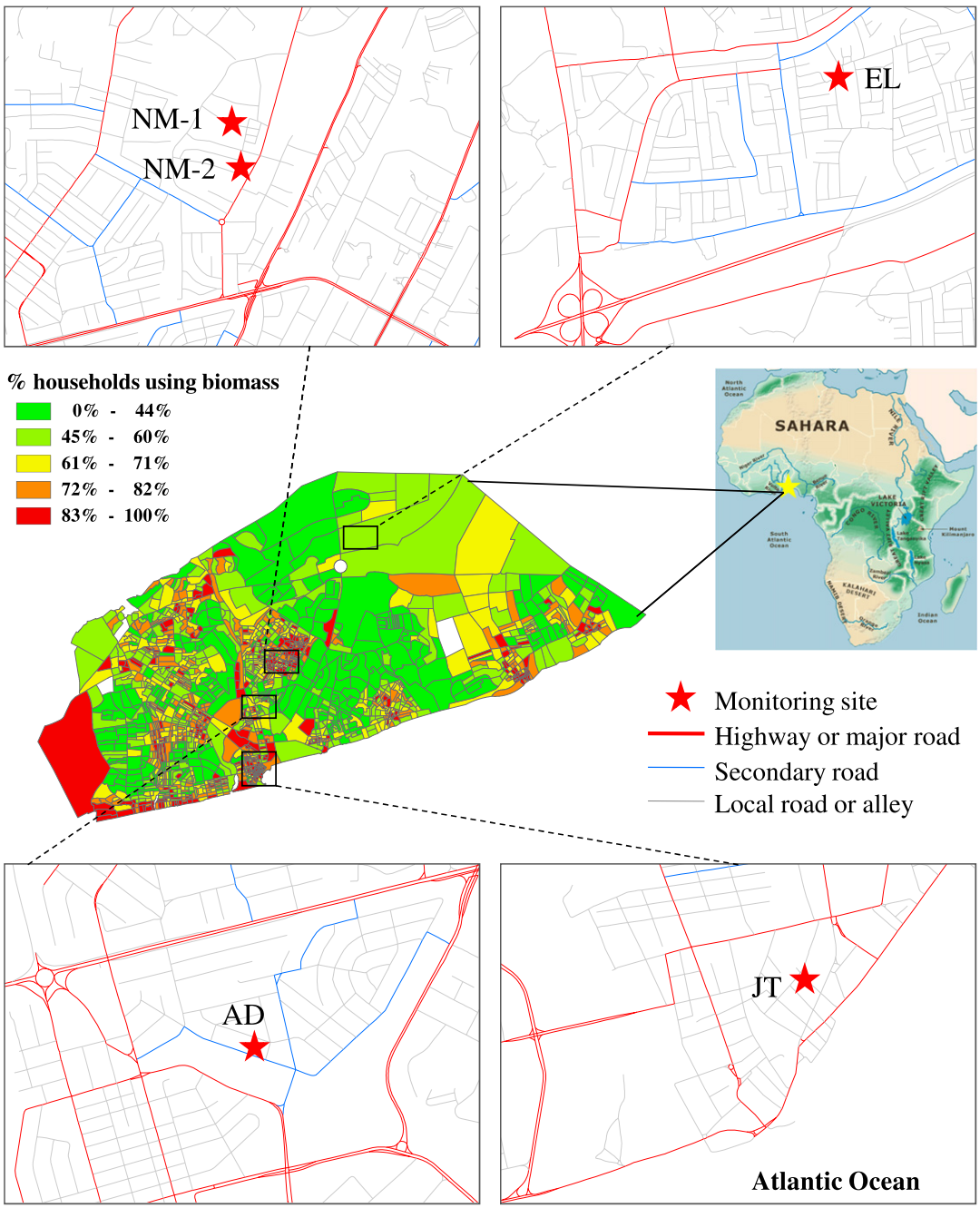


Figure 1. Study neighborhoods and measurement sites. The polygons on the central panel show census enumeration areas (EAs). Each EA has approximately the same population; hence the area of an EA is inversely related to population density. EAs are categorized according to quintile in terms of per cent of household using biomass fuels. Each color represents a different quintile. The sites were at locations that were typical of each neighborhood's living environment, with the EL site being far from major traffic and the AD site being next to a road with moderate traffic. In NM we also had a second site next to a road with heavy traffic. The distances of measurement sites to the ocean coast were: JT 0.5 km, AD 3 km, NM 4.5 km, and EL 9 km.

carbon, K, and SO_4^{2-} were also higher in JT, the neighborhood with the highest biomass use density (figure 1). K and SO_4^{2-} are linked to biomass burning and BC to emissions from combustion sources including biomass smoke. Potassium in biomass smoke is emitted mostly as potassium salts such as KCl and K_2SO_4; with aging, most KCl particles are converted to K_2SO_4 [11, 12].

Between 49% and 59% of PM_{10} mass was in the fine fraction at different sites (table 3). The proportion of mass in the fine fraction was below 40% for crustal oxides (MgO, Al_2O_3, SiO_2, CaO, TiO_2, MnO, and Fe_2O_3) and for elements in sea salt (Na and Cl), indicating that they were mostly in the form of coarse particles. In contrast, 60% or more of SO_4^{2-}, K, Ni, Zn, Br, Pb and BC mass was in the fine fraction, which can penetrate deeper into lungs. These elements are mainly associated with biomass and solid waste burning, motor vehicle emissions, and industrial sources.

There was strong correlation among the concentrations of crustal elements (tables S1 and S2, available at

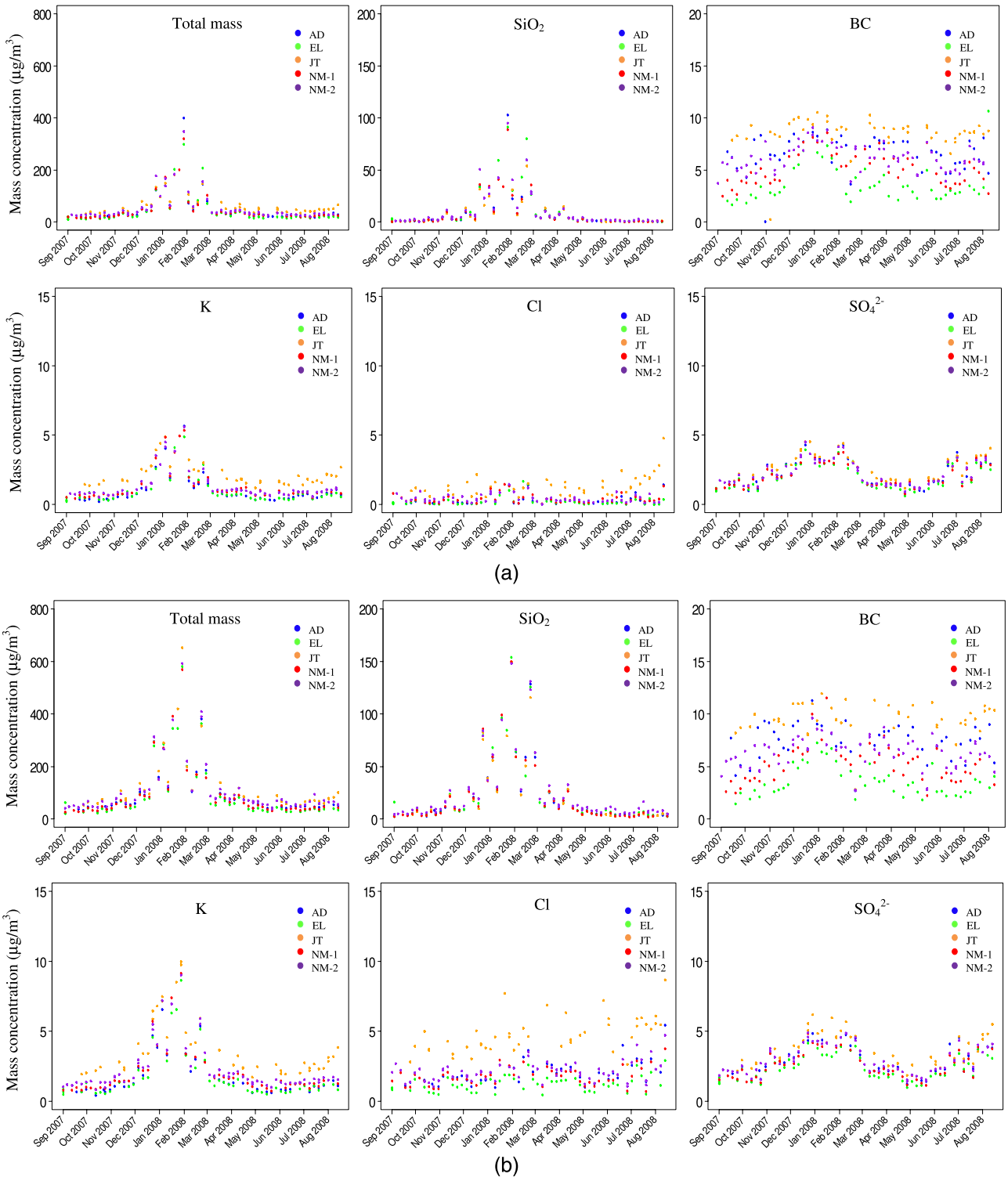


Figure 2. Concentrations of total particle mass and of selected elements for (a) $PM_{2.5}$ and (b) PM_{10} over the study period at the five measurement sites. Changes along the horizontal direction show variations over time and the spread along the vertical direction shows variation across measurement sites. For comparison, the World Health Organization (WHO) guideline for annual mean $PM_{2.5}$ concentration is 10 μg m^{-3}.

stacks.iop.org/ERL/8/044025/mmedia), especially during Harmattan (correlation coefficients ≥ 0.9), when the Saharan dust falls on the city. During Harmattan, crustal elements were also highly correlated with total particle mass. Sea salt elements (Na and Cl) were also correlated with one another in non-Harmattan months, when a sea breeze is more frequent. Similarly, there was moderate correlation among Br, Pb, and Zn, which are all present in vehicle emissions, tire and brake wear, road dust, and in smoke generated from burning solid waste [13, 14].

Table 1. Average concentrations of total $PM_{2.5}$ mass and its chemical components at five monitoring sites during the non-Harmattan months.

Chemical species	AD ($n = 35$)	EL ($n = 37$)	JT ($n = 36$)	NM-1 ($n = 39$)	NM-2 ($n = 52$)
Total mass[a]	27 ± 8	23 ± 8	50 ± 12	28 ± 8	34 ± 9
MgO	103 ± 128 (0.4%)[b]	141 ± 187 (0.6%)	179 ± 192 (0.4%)	125 ± 155 (0.5%)	132 ± 153 (0.4%)
Al_2O_3	909 ± 936 (3.4%)	1212 ± 1245 (5.4%)	1335 ± 1549 (2.6%)	1103 ± 1140 (4.0%)	1514 ± 1102 (4.4%)
SiO_2	2334 ± 2603 (8.6%)	3115 ± 3399 (13.8%)	3540 ± 4343 (7.0%)	2814 ± 3165 (10.2%)	3664 ± 2977 (10.7%)
CaO	319 ± 223 (1.2%)	351 ± 291 (1.6%)	543 ± 424 (1.1%)	404 ± 264 (1.5%)	635 ± 311 (1.9%)
TiO_2	53 ± 50 (0.2%)	68 ± 65 (0.3%)	75 ± 83 (0.1%)	64 ± 59 (0.2%)	93 ± 60 (0.3%)
MnO	10 ± 6 (<0.1%)	9 ± 7 (<0.1%)	11 ± 9 (<0.1%)	9 ± 7 (<0.1%)	12 ± 6 (<0.1%)
Fe_2O_3	495 ± 372 (1.8%)	604 ± 470 (2.7%)	594 ± 584 (1.2%)	534 ± 420 (1.9%)	771 ± 427 (2.3%)
SO_4^{2-}	1985 ± 778 (7.3%)	1815 ± 753 (8.1%)	2538 ± 829 (5.0%)	1894 ± 696 (6.8%)	2028 ± 726 (5.9%)
Na	295 ± 217 (1.1%)	239 ± 174 (1.1%)	502 ± 336 (1.0%)	284 ± 266 (1.0%)	226 ± 143 (0.7%)
K	585 ± 233 (2.2%)	633 ± 230 (2.8%)	1873 ± 414 (3.7%)	858 ± 248 (3.1%)	936 ± 232 (2.7%)
Cl	239 ± 269 (0.9%)	152 ± 119 (0.7%)	1450 ± 817 (2.9%)	346 ± 258 (1.2%)	366 ± 209 (1.1%)
V	1 ± 1 (<0.1%)	1 ± 1 (<0.1%)	1 ± 1 (<0.1%)	1 ± 1 (<0.1%)	1 ± 1 (<0.1%)
Cr	1 ± 1 (<0.1%)	1 ± 1 (<0.1%)	2 ± 1 (<0.1%)	1 ± 1 (<0.1%)	2 ± 1 (<0.1%)
Ni	4 ± 1 (<0.1%)	3 ± 1 (<0.1%)	4 ± 1 (<0.1%)	3 ± 2 (<0.1%)	3 ± 1 (<0.1%)
Cu	6 ± 5 (<0.1%)	2 ± 2 (<0.1%)	5 ± 4 (<0.1%)	5 ± 4 (<0.1%)	6 ± 6 (<0.1%)
Zn	38 ± 15 (0.1%)	15 ± 8 (0.1%)	45 ± 16 (0.1%)	29 ± 13 (0.1%)	32 ± 11 (0.1%)
Br	29 ± 22 (0.1%)	10 ± 4 (<0.1%)	36 ± 23 (0.1%)	23 ± 21 (0.1%)	23 ± 19 (0.1%)
Sr	2 ± 1 (<0.1%)	3 ± 2 (<0.1%)	4 ± 3 (<0.1%)	3 ± 2 (<0.1%)	4 ± 2 (<0.1%)
Zr	1 ± 1 (<0.1%)	2 ± 1 (<0.1%)	2 ± 2 (<0.1%)	1 ± 1 (<0.1%)	2 ± 1 (<0.1%)
Pb	14 ± 5 (0.1%)	6 ± 2 (<0.1%)	31 ± 15 (0.1%)	13 ± 4 (<0.1%)	14 ± 4 (<0.1%)
BC[c]	6603 ± 1642 (24.4%)	3676 ± 1774 (16.1%)	8613 ± 1509 (17.2%)	5176 ± 1584 (18.5%)	6200 ± 1268 (18.2%)
% of total mass accounted	52%	52%	43%	49%	49%

[a] Units are in ng m^{-3} except for total mass, which is in $\mu g\ m^{-3}$.

[b] Mean ± standard deviation. Numbers in parenthesis show the per cent of total mass.

[c] The 52 site-days with direct BC measurements using PM samples on quartz fiber filters also provided data on organic carbon (OC), measured following NIOSH Protocol 5040. For those 52 samples, OC accounted for 11–44% (mean 26%) of total PM mass. Mean OC/BC ratio in these samples was 1.7 (SD 0.6). In these samples, the correlation between OC and BC was around 0.6.

3.2. Source contributions

We identified 5–6 potential sources for fine particles and 4–5 for PM_{10} at different sites during non-Harmattan months (figure 3). The estimated contributions of sea salt to total $PM_{2.5}$ mass ranged between around 2 $\mu g\ m^{-3}$ in NM-2 and EL (4.5 and 9 km from the coast) to 13.9 $\mu g\ m^{-3}$ (25% of total $PM_{2.5}$ mass) in JT (500 m from the coast) during non-Harmattan months. Similarly, sea salt contribution to PM_{10} was smallest in EL and largest in JT, accounting for 6.4 $\mu g\ m^{-3}$ (14%) and 27.5 $\mu g\ m^{-3}$ (31%) of total PM_{10} mass, respectively. In contrast to sea salt, crustal sources made up a larger share of total particle mass in EL, the northernmost neighborhood. For example 38% of $PM_{2.5}$ and 46% of PM_{10} mass in EL were from crustal sources, compared to only 17% and 16% in JT. Despite having a larger share from crustal sources, lower total particle mass in EL meant that the absolute contribution of crustal aerosols was only slightly higher than other neighborhoods, e.g., 10.5 $\mu g\ m^{-3}$ in $PM_{2.5}$ compared to 9.5 $\mu g\ m^{-3}$ in JT. This higher absolute contribution may have been because more spread-out low-rise homes do not block the windblown Saharan or local dust.

Biomass smoke contributed more particle pollution in NM and JT, where the density of households who use biomass fuels is substantially higher [6], than in AD and EL; biomass-related particles accounted for 15.7–21.3 $\mu g\ m^{-3}$ of $PM_{2.5}$ mass in the former two neighborhoods, compared to 10.6 $\mu g\ m^{-3}$ in AD and 11.2 $\mu g\ m^{-3}$ in EL. Road dust and traffic aerosols had a more important role in the two sites near traffic routes, one of NM's sites by a busy road and the AD site. A last source, which is likely to be burning of solid waste, was identified for fine particles in all neighborhoods except affluent EL, being largest in JT where old tires and other solid waste are commonly burned.

There was about 10 times as much particle mass from crustal sources during Harmattan as there had been in other months (figure 3). During Harmattan, there was also an increase in particle pollution from resuspended road dust and from biomass burning. The absolute amount of particle mass from other sources changed little, leading to a reduction in their share of total mass.

4. Strengths and limitations

To our best knowledge, this paper uses one of the richest data sets on particle air pollution levels, chemical composition, and sources in a developing country city. The unique data come from our own measurements in poor and affluent neighborhoods and in different seasons, combined with data from the Population and Housing Census and the Survey Department, all with detailed geospatial information. The consistent and comparable data in poor and affluent neighborhoods alone allow us to examine, for the first time,

Table 2. Average concentrations of total PM_{10} mass and its chemical components at five monitoring sites during the non-Harmattan months.

Chemical species	AD ($n = 33$)	EL ($n = 37$)	JT ($n = 33$)	NM-1 ($n = 40$)	NM-2 ($n = 54$)
Total mass[a]	55 ± 18	46 ± 19	81 ± 22	51 ± 20	70 ± 21
MgO	454 ± 289 (0.8%)[b]	446 ± 342 (1%)	741 ± 346 (0.9%)	430 ± 335 (0.8%)	515 ± 329 (0.7%)
Al_2O_3	3026 ± 2220 (5.5%)	3646 ± 2516 (7.9%)	3088 ± 2626 (3.8%)	3239 ± 2535 (6.3%)	4882 ± 2780 (7.0%)
SiO_2	8484 ± 6441 (15.5%)	9749 ± 7245 (21.1%)	8764 ± 7635 (10.8%)	8744 ± 7126 (17.0%)	12 270 ± 7374 (17.6%)
CaO	1520 ± 788 (2.8%)	1340 ± 804 (2.9%)	2260 ± 1023 (2.8%)	1682 ± 958 (3.3%)	2653 ± 1127 (3.8%)
TiO_2	212 ± 140 (0.4%)	233 ± 151 (0.5%)	215 ± 159 (0.3%)	218 ± 154 (0.4%)	343 ± 182 (0.5%)
MnO	26 ± 15 (<0.1%)	24 ± 17 (0.1%)	27 ± 18 (<0.1%)	25 ± 16 (<0.1%)	35 ± 18 (0.1%)
Fe_2O_3	2096 ± 1060 (3.8%)	2171 ± 1110 (4.7%)	1783 ± 1169 (2.2%)	1956 ± 1210 (3.8%)	2895 ± 1261 (4.1%)
SO_4^{2-}	2601 ± 847 (4.7%)	2138 ± 682 (4.6%)	3301 ± 879 (4.1%)	2276 ± 737 (4.4%)	2625 ± 758 (3.8%)
Na	1033 ± 624 (1.9%)	616 ± 463 (1.3%)	2021 ± 838 (2.5%)	739 ± 505 (1.4%)	739 ± 505 (1.4%)
K	880 ± 332 (1.6%)	874 ± 328 (1.9%)	2188 ± 490 (2.7%)	1123 ± 354 (2.2%)	1324 ± 356 (1.9%)
Cl	2023 ± 930 (3.7%)	1203 ± 570 (2.6%)	4871 ± 1362 (6.0%)	1711 ± 658 (3.3%)	2087 ± 733 (3%)
V	3 ± 1 (<0.1%)	3 ± 1 (<0.1%)	2 ± 1 (<0.1%)	2 ± 2 (<0.1%)	3 ± 2 (<0.1%)
Cr	4 ± 1 (<0.1%)	4 ± 1 (<0.1%)	4 ± 2 (<0.1%)	3 ± 2 (<0.1%)	5 ± 2 (<0.1%)
Ni	3 ± 1 (<0.1%)	3 ± 1 (<0.1%)	3 ± 1 (<0.1%)	3 ± 1 (<0.1%)	3 ± 1 (<0.1%)
Cu	10 ± 5 (<0.1%)	4 ± 2 (<0.1%)	8 ± 4 (<0.1%)	8 ± 3 (<0.1%)	11 ± 5 (<0.1%)
Zn	55 ± 18 (0.1%)	26 ± 13 (0.1%)	71 ± 27 (0.1%)	41 ± 18 (0.1%)	55 ± 16 (0.1%)
Br	35 ± 24 (0.1%)	12 ± 5 (<0.1%)	44 ± 21 (0.1%)	28 ± 23 (0.1%)	32 ± 24 (<0.1%)
Sr	8 ± 4 (<0.1%)	8 ± 5 (<0.1%)	14 ± 6 (<0.1%)	10 ± 5 (<0.1%)	13 ± 6 (<0.1%)
Zr	5 ± 4 (<0.1%)	6 ± 4 (<0.1%)	5 ± 4 (<0.1%)	5 ± 4 (<0.1%)	8 ± 4 (<0.1%)
Pb	22 ± 6 (<0.1%)	9 ± 3 (<0.1%)	36 ± 14 (<0.1%)	17 ± 5 (<0.1%)	21 ± 5 (<0.1%)
BC	7407 ± 1664 (13.5%)	3617 ± 1450 (7.8%)	9587 ± 1463 (11.8%)	5358 ± 1884 (10.5%)	6283 ± 1476 (9.0%)
% of total mass accounted	54%	57%	48%	54%	53%

[a] Units are in ng m^{-3} except for total mass, which is in μg m^{-3}.

[b] Mean ± standard deviation. Numbers in parenthesis show the per cent of total mass.

how air pollution levels, composition, and sources differ in relation to socioeconomic status.

Similar to all field measurement studies, our work is affected by some limitations. Logistical difficulties and time-intensive field work restricted our ability to run multiple measurement sites simultaneously in each study neighborhood to assess within-neighborhood variation. It would have been desirable to conduct consecutive 48 h measurements, but this was beyond our resources.

Limitations in the analysis include the reliance of source apportionment analysis on relatively stable source profiles across samples. In reality, source profiles may somewhat differ overtime, even at the same site. The choice of the number of PM sources is based on the best compromise between the goodness of model fit and the physical meaningfulness of the resolved factors; we tried the source apportionment with different numbers of factors and compared the results before selecting the current number of sources. In addition, labeling PM sources after PMF analysis also involves some subjectivity. All of these limitations should inform the design of future research on the sources of urban air pollution in cities in low- and middle-income countries where combustion and non-combustion sources are changing relatively rapidly.

5. Discussion and conclusions

Our findings on the chemical composition and sources of air pollution provide a number of important directions for air pollution control in rapidly expanding developing country cities like Accra. First, the role of urban biomass burning as a source of air pollution creates both policy complexities and opportunities. Large-scale transitions to cleaner fuels such as liquefied petroleum gas (LPG) may require targeted subsidies for fuel and/or financial assistance towards the initial cost of an LPG stove for poor households. Perhaps more importantly, sustained use of clean fuels requires improving the energy delivery and distribution infrastructure so that people can have regular trouble-free access to fuel purchase, currently not available in poor neighborhoods [6]. On the other hand, addressing household fuel use in cities can take advantage of high population density and urban infrastructure versus in rural areas, where long distances and poor roads and energy infrastructures make fuel switching more challenging. In addition to urban biomass use, long-range transport of particles from wild bushfires or from land clearing/preparation for agriculture by burning may be responsible for urban particle pollution in West Africa [16]. Reducing regional biomass pollution requires attention to land use and agriculture policies and should be accompanied by local strategies for wildfire management [17].

Second, while resuspended dust may seem outside the realm of policy interventions, local and regional strategies do exist: road and urban dust can be addressed through paving roads, traffic control, and, where affordable, regular road cleaning. Regional dust pollution is intensified by deforestation and desertification, and can be gradually reduced through afforestation and grassland restoration [18–21].

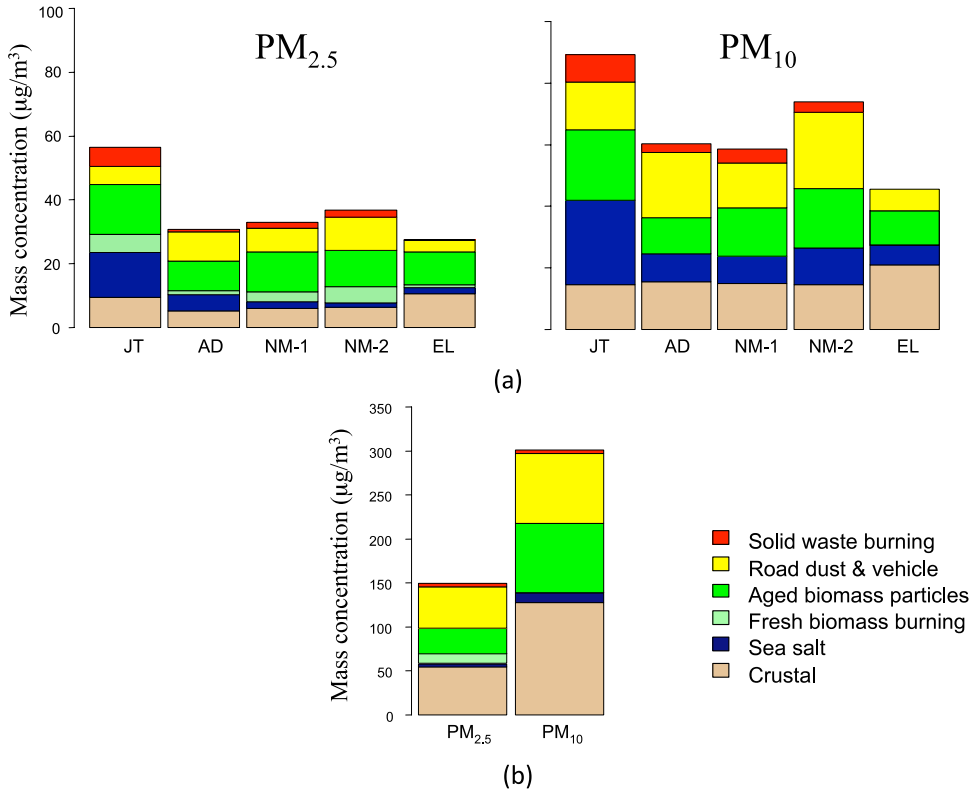


Figure 3. Contributions of pollution sources to particle mass during (a) non-Harmattan months, by neighborhood and (b) peak Harmattan (25 December 2007 to 30 January 30 2008). Sea salt is characterized primarily by Na, Cl, and S (in aged sea salt, the Cl ion is replaced by SO_4^{2-} as a result of reaction with sulfuric acid; this chemical transformation is more pronounced in coastal areas than in inland regions [15]). Crustal sources are characterized by Si, Al, Mg, Ti, Mn and Fe. Biomass smoke is primarily characterized by K, Cl, S, and black carbon (BC) [12]. Road dust and traffic particles are characterized by Al, Si, Ca, Fe, and BC. Solid waste burning is characterized by Br [14]. During Harmattan, data from the five sites were pooled to increase sample size, after confirming that source profiles (but not contributions) were similar across sites.

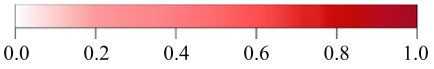
Beyond ecological considerations, such strategies should be connected with programs related to population growth and mobility, and those that improve the economic conditions of rural households who rely on land resources. The important role of seasonal dust as a pollution source also demonstrates the need for research on the acute and chronic health effects of exposure to crustal particles [22, 23], and whether air pollution regulations in developing countries should be based on total particle mass or specifically target combustion sources.

Third, while traffic sources accounted for a relatively small share of particle pollution in Accra, their absolute contribution towards $PM_{2.5}$ was over 10 μg m^{-3} in some neighborhoods, larger than WHO guidelines for total $PM_{2.5}$ concentration. If African cities follow Asian and Middle Eastern megacities, where traffic management and pollution is a major policy challenge, there will be even more traffic-related pollution. Curbing and reducing traffic air pollution will inevitably require a sustainable pro-poor public transportation system, as implemented in cities like Bogota [24]. African countries are a market for old cars that do not meet emissions standards in Europe and North America [25]. While the lower cost of used vehicles may help meet transportation needs in low-resource settings, there is a need to assess whether their economic benefits outweigh their health hazards, especially if the harms disproportionately affect poor urban communities relative to the benefits. Fourth, there was a larger contribution from burning of solid waste in poor neighborhoods, where trash collection is less frequent than in affluent neighborhoods. This demonstrates the need for equitable provision of urban services, now largely absent from poor slums.

Air pollution regulation and technological advances related to emissions from vehicles, power plants, and factories, have led to cleaner cities in high-income countries. Some cities have also benefited from reducing pollution from local or regional dust, for example through sweeping and washing roads, stabilizing the road surface with dust suppressants, and planting trees. Lower particle pollution has in turn contributed to improved health [26]. The highest pollution levels, and about 90% of the global disease burden from air pollution, now occur outside the Americas and Europe [1, 27]. Therefore, while efforts to further reduce air pollution in these regions continue, there is an urgent need to tackle air pollution in cities in the developing world. The diversity of sources demonstrates the need for integration of policies and interventions across environment, energy, transportation, urban development and even forestry and agriculture sectors, while explicitly considering the benefits and harms of each strategy for poor communities. The

Table 3. Average $PM_{2.5}$-to-PM_{10} ratio of total PM mass and its chemical components at five monitoring sites during the non-Harmattan season.

Species (*n*)	AD (33)	EL (34)	JT (40)	NM-1 (36)	NM-2 (60)
Total mass	0.50	0.50	0.59	0.54	0.49
MgO	0.24	0.28	0.14	0.25	0.24
Al_2O_3	0.28	0.29	0.28	0.31	0.28
SiO_2	0.24	0.26	0.23	0.27	0.26
CaO	0.20	0.23	0.20	0.22	0.23
TiO_2	0.23	0.25	0.21	0.26	0.25
MnO	0.39	0.36	0.34	0.37	0.34
Fe_2O_3	0.22	0.26	0.23	0.25	0.25
SO_4^{2-}	0.73	0.80	0.74	0.78	0.75
Na	0.27	0.38	0.22	0.33	0.28
K	0.63	0.71	0.81	0.77	0.71
Cl	0.09	0.11	0.25	0.17	0.15
V	0.37	0.41	0.45	0.37	0.36
Cr	0.38	0.40	0.35	0.31	0.30
Ni	0.82	0.67	0.84	0.72	0.82
Cu	0.54	0.31	0.49	0.41	0.48
Zn	0.68	0.59	0.68	0.70	0.59
Br	0.77	0.75	0.71	0.78	0.78
Sr	0.30	0.37	0.27	0.30	0.29
Zr	0.24	0.28	0.31	0.31	0.22
Pb	0.68	0.70	0.85	0.73	0.70
BC	0.89	1.00	0.90	0.97	0.99



post-2015 Development Agenda provides an opportunity for such integration if urban environment and urban poverty take a central role in the discussions and the recommended policies and related targets.

Acknowledgments

We thank the residents of Jamestown/Ushertown, Asylum Down, Nima, and East Legon for their hospitality; Nana Prempeh and Adam Abdul Fatah for field assistance; and the Legal Resources Center and the Department of Geography and Resource Development at the University of Ghana for valuable help with logistical arrangements. Funding for field data collection was provided by National Science Foundation Grant 0527536, and laboratory support was provided by the Harvard National Institute on Environmental Health Sciences Center for Environmental Health. Majid Ezzati is supported by a UK MRC Strategic Award. This research was approved by Institutional Review Boards of the Harvard School of Public Health and Noguchi Memorial Institute for Medical Research at the University of Ghana.

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