ARTICLE IN PRESS

Atmospheric Pollution Research xxx (2016) 1–15

Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: http://www.journals.elsevier.com/locate/apr

Source apportionment analyses for fine ($PM_{2.5}$) and coarse ($PM_{2.5-10}$) mode particulate matter (PM) measured in an urban area in southwestern Nigeria

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A R T I C L E I N F O

Article history:
Received 14 January 2016
Received in revised form
22 April 2016
Accepted 23 April 2016
Available online xxx

Keywords:
$PM_{2.5}$
XRF
Source apportionment
PMF model
CPF
Vehicular emissions
Urban aerosol

A B S T R A C T

To determine the influence of regional and local sources of the fine and coarse fractions of airborne particulate matter (PM), samples were collected in 2006, 2007, 2010, and 2013 covering the 2 major seasons (wet and dry) at multiple locations in Ile-Ife, Nigeria. A total of 216 samples for each of the $PM_{2.5}$ and $PM_{2.5-10}$ were collected on polycarbonate filters using low volume Gent samplers. Elements and black carbon was measured using x-ray fluorescence (XRF) spectrometry and optical transmissometry, respectively. The average mass concentration for the $PM_{2.5}$ and $PM_{2.5-10}$ at Obafemi Awolowo University (OAU) in 2006, 2007, and 2010 exceeded the annual National Ambient Air Quality Standards (NAAQS) of 15 and 60 $\mu g/m^3$ for $PM_{2.5}$ and $PM_{2.5-10}$, respectively. At the Obafemi Awolowo University Teaching Hospital Complex (OAUTHC) sites, the $PM_{2.5}$ and $PM_{2.5-10}$ mass fractions also exceeded the NAAQS standards except at the urban background site. Positive matrix factorization (PMF) was used to identify and apportion the PM sources for the combined data from these sampling sites. Four sources each were identified for both $PM_{2.5}$ and $PM_{2.5-10.}$ The sources are soil (44%), savannah burning (26%), scrap processing (18%) and vehicular emissions (12%) for $PM_{2.5}$ and soil plus biomass burning (71%), sea salt (22%), scrap processing (5%) and vehicle emissions (tire wear) (2%) for $PM_{2.5-10}$. Most of the PM mass originated from anthropogenic contributions. The highest contributions were associated with northwesterly wind from the urbanized areas of Ile-Ife.

1. Introduction

Particulate matter (PM) degrades air quality as a result of increased industrialization and growth in human population. PM has been strongly linked with serious detrimental human health effects including decrease in life expectancy, increased morbidity and mortality, lung cancer, chronic respiratory and heart diseases (Dockery and Pope, 1994; Kampa and Castanas, 2008; Pope and Dockery, 2006), global warming (Flanner et al., 2007; Racherla and Adams, 2006) and damage to vegetation (Adole, 2011; Dung et al., 2008).

PM includes carbonaceous species that can be characterized as organic carbon (OC) and black carbon (BC) constituting a major, and sometimes dominant fraction of atmospheric PM (Ng et al., 2010). Black carbon is the principal light-absorbing constituent in the atmosphere, playing an important role in the aerosol climatic forcing (Jacobson, 2002; Bond et al., 2013). It may contribute significantly to both visibility degradation and the direct aerosol climatic forcing (Malm et al., 2000; Bond et al., 2013). Visibility reduction due to the presence of Saharan PM in the atmosphere is a common feature in most parts of sub-Saharan West Africa between the months of November and March, known as the Harmattan period. It is characterized by massive deposition of dust particles

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Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

http://dx.doi.org/10.1016/j.apr.2016.04.006

originating from the Sahara Desert. During this season, the inter-tropical discontinuity (ITD) is displaced southwards such that virtually all parts of sub-Saharan West Africa, including Nigeria, Benin, Togo, Ghana, and Ivory Coast between the Sahel and the Gulf of Guinea are under the influence of the northeast (NE) trade wind that transports Saharan dust into most parts of the region. It contributes large fractions to the fine particulate mass (Kirchstetter et al., 1999; Ofosu et al., 2013).

To effectively reduce the concentrations and hence mitigate the effects of particulate air pollution, there is the need to be able to identify the sources of the pollutant and be able to quantify the contribution from these sources with a reasonable degree of accuracy. Source apportionment methods have thus been developed for this purpose. Several models have been devised and employed in this regard and many of them have been successful at carrying out the source identification and apportionment of the pollutants. These models include chemical mass balance (CMB) (Bullock et al., 2008; Shi et al., 2011), Unmix (Murillo et al., 2012; Norris et al., 2007) and positive matrix factorization (PMF) (Juntto and Paatero, 1994; Lee et al., 1999; Hopke, 2016).

PMF takes into consideration the uncertainties in the data and produces non-negative factor loadings and scores. With the careful selection of the modeling parameters, PMF has been found to be more powerful in source identification than the other factor analysis techniques (Huang et al., 1999; Hien et al., 2004). PMF has become the most widely used source apportionment method (Bellis et al., 2013; Hopke, 2016). PMF can resolve the dominant positive factors without the prior knowledge of the sources and provides the source profiles and the time series of the source contributions (Paatero, 1997; Oh et al., 2011; Paatero et al., 2014). It has been previously applied to data from Ghana in which Harmattan dust has been observed to be dominant (Ofosu et al., 2013). Hence, this model will be appropriate to identify and estimate the contributions of distant savannah burning/Harmattan dust to the air quality in the sub-Saharan region.

The present study provides information that will be useful in formulating an air management framework to address the influence of regional and local sources of $PM_{2.5}$ and $PM_{2.5-10}$ on urban areas in sub-Sahel West Africa and more importantly in Nigeria where air quality is poor and unhealthy (Obioh et al., 2013).

2. Materials and method

2.1. Study area

Ile-Ife is a university town in southwestern Nigeria. It is an ancient town with a population of about 502,000 (Ajala and Olayiwola, 2013). The town houses two large Federal institutions: the Obafemi Awolowo University (OAU) founded in 1962 on an isolated expanse of land estimated to be about 11,861 Hectares (http://www.oauife.edu.ng/about-oau) and the Obafemi Awolowo University Teaching Hospital Complex (OAUTHC) at latitude 7.500° N and Longitude 4.540° E. A scrap iron and steel smelting plant is about 5 km away from OAU along the major Ife-Ibadan Road. There are other inter-campus roads within OAU campus with one of them linking the expressway. While the University is a town on its own and largely isolated from Ile-Ife town, the tertiary OAUTHC is located such that it is bounded by dense residential areas, left, right and front with the University at a distant back. The presence of these two institutions in the town has drastically affected the volume of traffic on the major roads on a daily basis, especially during the morning and evening rush hours.

There are two broad seasonal patterns experienced in the study area: the dry (November–March) and rainy (April–October) season. The dry season features brief intervals, known locally as the Harmattan periods, when cold and dust-laden north-easterly trade winds from the Sahara desert transport significant quantities of dust for multiple days. The period is usually dry with high solar radiation and clear sky conditions, moderate air temperatures and no precipitation. However, in coastal areas, the sea breeze during the Harmattan period often sets in around noon (Rosser and Imray, 1869; Knox, 1911). Between April and mid-October, the near surface flow is dominated by the southwesterly winds originating from the Atlantic Ocean (Akinlade et al., 2015).

A 3-week (13 March – 6 April, 2013) vehicular count conducted by some undergraduate students attached to the Environmental Research Laboratory (ERL) of the Physics Department, OAU on a major single-lane road around OAUTHC revealed that the mean hourly vehicular count can be as much as 2,015, comprising 1350 cars, 630 two-wheeled motorcycles, and 35 heavy duty lorries. On average, the weekday daily (12-hour day) vehicular count of 25,000 was estimated for the major road in the study area.

This study was intended to assess the contribution of Harmattan dust and traffic to the level of pollution in the premises of the tertiary health facility. The sampling points were situated at least 1 km from one another downwind of the suspected pollution sources. Fig. 1 shows the satellite image of the study site with the sampling points.

2.2. Sampling and gravimetric analysis

The sampling on the roof of the two-story Physics Building at OAU was for the periods of December, 2006, January–February and November–December, 2007 (Harmattan period) and January–August, 2010 (Harmattan period: January–March and non-Harmattan period: April–August) three times in a week (Table 1). The sampling platform was 15 m (approx.) above the ground and about 294 m above sea level. It is located in the tropical rainforest zone at latitude 7.520° N and longitude 4.520° E. This location lies in an open space that is not obstructed by objects or buildings as shown in Fig. 1.

The 2013 sampling campaign was performed because of the surge in traffic density. The heavy traffic during the early and closing hours every working day necessitates the need to determine the effect of traffic on the PM within the tertiary OAUTHC. The three sampling sites are shown in Fig. 1 and are labeled as Auditorium (Lat. 7.500° N, Lon. 4.540° E), Phase 1 (Lat. 7.490° N, Lon. 4.570° E) and Phase 2 (background, Lat. 7.500° N, Lon. 4.560° E). The sites were strategically chosen due to the access to availability of electricity for the period of sampling between January to July, 2013 with a very brief Harmattan period in January. The sampling campaign was started at the sites designated in Fig. 1 after a site survey based of the intensity of activities around each location, the degree of obstruction, and representativeness of the sites of likely high and low polluted areas within the study area. The availability of electricity and security were also considered. Thus, the premises of OAUTHC were chosen for the work. At the time of sampling, only two low-volume Gent samplers were available and deployed to the study site for the seven-month period. The sampler used at the Auditorium site was moved to Phase 2 site in May, 2013 in order to have information at the control site (Table 1).

The 24-hour sampling was conducted three times each week, Mondays, Wednesdays and Fridays from January to July 2013. The Gent samplers were equipped with a stack filter unit (SFU) capable of collecting two fractions of the fine or coarse PM ($PM_{2.5}$ and $PM_{2.5-10}$). The SFU holds two 47 mm polycarbonate filters of 8.0 and 0.4 μm pore size for collecting $PM_{2.5-10}$ and $PM_{2.5}$, respectively (Hopke et al., 1997; Maenhaut et al., 1993). Air was sampled at an average rate of 16 L/min (approx.) and at this rate, the unit should act as a dichotomous sampler. Airflow through the 8-μm pores will

Please cite this article in press as: Owoade, K.O., et al., Source apportionment analyses for fine ($PM_{2.5}$) and coarse ($PM_{2.5-10}$) mode particulate matter (PM) measured in an urban area in southwestern Nigeria, Atmospheric Pollution Research (2016), http://dx.doi.org/10.1016/j.apr.2016.04.006