Bull Environ Contam Toxicol (2008) 81:190–195
DOI 10.1007/s00128-008-9453-2

Source Apportionment of PM10 in Mumbai, India Using CMB Model

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Received: 11 December 2007 / Accepted: 24 April 2008 / Published online: 24 May 2008

Abstract Source apportionment study is carried out to identify the sources of particulate matter of size less than 10 μm in Mumbai using chemical mass balance model. Various locations representing different activity zones as low activities (control), normal activity including commercial and residential areas and traffic sites (kerbside) are selected for this purpose to represent the city. It is observed that at control sites industrial contributions prevail, the other significant contributions are from marine and vehicular activities. At normal activity sites, vehicular, industrial and soil dust contributions are observed to be dominant. At two of the kerbside sites, marine contributions are observed to be significant which was due to the proximity of the sites to sea. The vehicular and soil dust contributions are observed to be significant at remaining kerbside sites. The study is useful for preparing the particulate matter reduction action plan for Mumbai, which can be extended further to other cities of India.

Keywords Particulate matter · Source apportionment · Chemical mass balance

Particulate matter in ambient air has been a matter of concern due to its ill-effects on human health and environment (Schwartz et al. 1996). Due to increase in population and number of vehicles, the particulate pollution is increasing in the cities of India. The problem is even worse in metropolitan cities. Although several control measures have been initiated in mega cities of India, the implementation of these control measures has however not resulted in the reduction of particulate matter to that extent as expected (Centre for Science and Environment 2001). To curb the problem, it is necessary to identify the sources from which the high levels of particulate matter originate. The source apportionment of particulate matter has been carried out all over the world to identify the major significant sources (Breed et al. 2002; Samara et al. 2003; Watson and Samara 2005). In India there are very few studies carried out to identify the sources of particulate matter specifically for the particulates with size less than 10 (PM10) and 2.5 (PM2.5) μm (Sharma and Patil 1994; Shah and Nagpal 1997; Vinodkumar et al. 2001; Tripathi et al. 2004; Chelani et al. 2005; Srivastava and Jain 2007; Gupta et al. 2007). The source apportionment is generally carried out by using receptor modeling techniques. There are many receptor models such as enrichment factor (EF) analysis, chemical mass balance (CMB), factor analysis (FA), empirical orthogonal functions (EOF), multiple linear regression, neural networks, edge detection and cluster analysis. Among these, the CMB model is most trusted for the coarse and fine particle source apportionment (USEPA 1997). The CMB model estimates source contributions by determining the best linear combination of emission source profiles and the chemical composition of ambient PM10 samples (Watson et al. 1991). In Indian context, the studies on source apportionment by CMB are limited and factor analysis technique is widely used (Sharma and Patil 1994; Vinod Kumar et al. 2001; Chelani et al. 2005; Gupta et al. 2007; Srivastava and Jain 2007). The study is therefore, attempted to quantitatively apportion the sources of PM10 concentrations using CMB model in Mumbai, which is one of the metropolitan cities of India with a population of approximately 12 million in 2001.

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Mumbai, located at the coast of Arabian sea in west India, has a tropical savanna climate with relative humidity ranging between 57% and 87%, and annual average temperature of 25.3°C. The average annual precipitation is 2,078 mm, with 34% of total rainfall occurring in July. The prevailing wind directions are from west and northwest, with west and southwest shifts during monsoon and east during winter. As Mumbai experiences high concentrations of PM10 exceeding the ambient air quality standards, it is important to identify the contributing emissions sources. The past studies carried out in India for particulate matter source apportionment are restricted to one or few activity zones (Vinodkumar et al. 2001; Tripathi et al. 2004; Gupta et al. 2007). It is important to understand the contribution of emission sources of PM10 at various locations representing different activities in an urban area to formulate effective control measures. In order to represent the city, the locations representing different activity zones as control, normal activity including residential and commercial activities and curbside are selected.

Materials and Methods

The air quality status is determined in three activity zones namely low activity (Control), normal activity (Ambient air quality) and high traffic density (Curbside). Eleven sites are selected to represent different segments of the region, which include two control/reference, four normal activity (industrial, commercial, residential) and five curbside sites. Sampling locations are shown in Fig. 1 (NEERI 2004) and described in Table 1. Prior to air sample collection; preparatory conditioning procedures were applied to filters. They were kept in desiccators. Filters were taken to the sampling sites in a container without exposure to ambient air. After completing sample collection, filters were put back into desiccators until analyses were performed. Twenty four hourly sampling was carried out round the clock using respirable high volume sampler with a flow rate of 1 m^3 min^{-1}. The PM10 samples were collected on glass fibre filter paper twice in a week continuously during the winter season (December 2001–February 2002). PM10 collected on glass fibre filter paper is determined by gravimetric method. Separate analysis for each of the sites representing different activity zones is conducted for various prerequisite variables. The variables used for the analysis are organic carbon (OC) as benzene soluble fractionate (BSF), Cl, K, SO_4, NO_3, F, Zn, Pb, Ni, Fe, Cr, Cu, Sr, V, B, Ba, Ca, Mg, Cd, Co, Na, Mn, Al, Ba. The PM10 samples collected during air quality monitoring are characterized for the ions by Ion Chromatography and metals by Inductively Coupled Plasma Atomic Emission Spectrometric technique (Katz 1977).

For source apportionment of PM10, CMB 8.0 software (USEPA 1997) is used. It is windows based software that provides many goodness of fit tests to verify the accuracy of the model. The normal checks, as specified in the manual by USEPA (1997) to accept the model are; *t*-statistics i.e., source contribution divided by error of source contribution should be greater than 2, χ^2 should be less than 4, R^2 should be greater than 0.8, percentage mass explained should be between 80% and 120%, the ratio of computed and measured concentration of each element (C/M ratio) should be close to 1 and R/U ratio, i.e., the ratio of residuals to uncertainty should be less than 2. As the model requires the source contribution estimates and receptor concentrations in ambient air, the significant sources in the area needs to be identified first. The investigation of sources of PM10 to be accounted far in CMB model is carried out using emission inventory studies (NEERI 2004; Bhanarkar et al. 2005). The major air pollution sources in the city are industries, domestic combustion, crematoria, bakeries, construction and vehicular traffic. As per the estimated emission inventory prepared for Mumbai, total contribution of PM emission from all sources is 16550.5 tonnes/year. There are a total 183 industries contributing approximately 44.2% of PM each year (NEERI 2004). Another source of particulate matter emissions in Mumbai is vehicular activities. The particulate matter emitted from all types of vehicles is estimated to be 1,854 tonnes/year. The domestic source also plays an important role in contributing PM emissions. The slum population ($\sim$28.5% of total population in Mumbai) mainly uses kerosene and wood, whereas remaining 71.5% population uses LPG. The total LPG consumption during the year 2000–2001 in domestic and commercial zones is reported to be 2,36,052 MT and 18,512 MT, respectively. The total emissions of PM from domestic sources have been estimated to be 2,235 tonnes/year, respectively. The total emission of PM from area sources is 3986.10 tonnes/year. The total PM10 load due to building construction is 420.25 tonnes/year and due to road construction activities is 388.64 tonnes/year. The major sources identified thus include resuspension of soil dust, vehicular exhaust, combustion, sea salt/marine and industrial emissions. The respective source profile of each source is taken from USEPA SPECIATE 3.2 data base.

Results and Discussion

It is observed that average PM10 concentration varies from 76–114 μg m^{-3} at control site, 126–318 μg m^{-3} at curbside, 72–159 μg m^{-3} at AAQ sites. The average concentrations of PM10 at each site are given in Table 2a and 2b. The minimum PM10 concentration is observed at

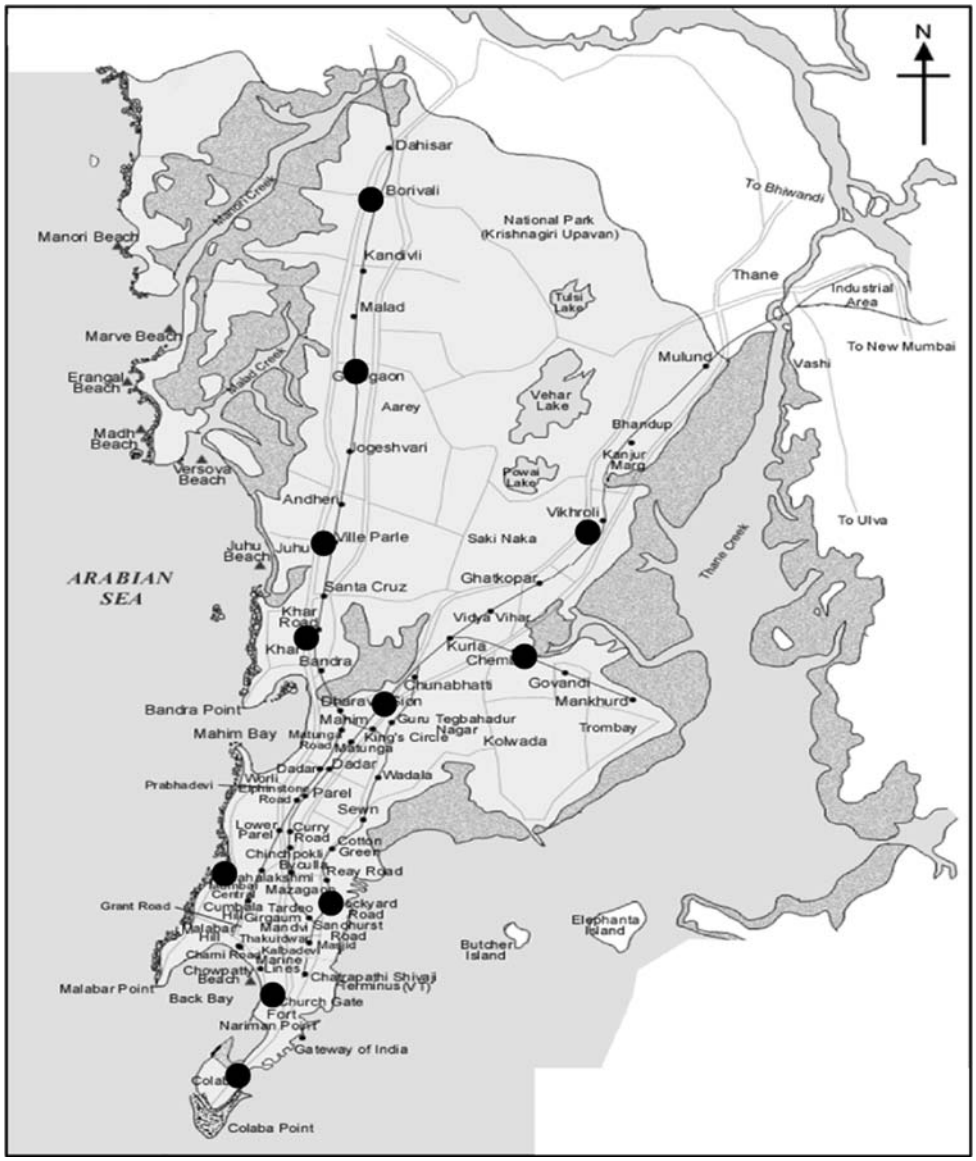

Fig. 1 Location of sampling sites

Table 1 Description of sampling sites

Site	Classification	Refer as	Description
Colaba	Control	C1	No traffic, near to coast
Borivali	Control	C2	Residential area, minimum traffic
Haji Ali	Curbside	K1	Sea shore on one side, 4 road-junction,
Metro	Curbside	K2	Commercial area, 6 road-junction
Sion	Curbside	K3	Commercial area with heavy traffic
Chembur	Curbside	K4	Commercial area, 6 lane road, traffic
Villeparle	Curbside	K5	Busy road, civil air port, bus depot
Mazogaon	Air quality	AAQ1	Heavy traffic, dockyard activity
Khar	Air quality	AAQ2	Four lane road, heavy traffic, commercial area
Goregaon	Air quality	AAQ3	Residential, moderate traffic
Vikhroli	Air quality	AAQ4	Moderate traffic, commercial activity

AAQ3 site with low variability. The next minimum concentration is observed at C1. Comparing the curbside stations, the minimum concentration is observed at K1, whereas highest concentration of PM10 is observed at K5. The concentration of species of PM10 is also compared. The highest concentration of BSF at K5 indicates the high

Table 2 Chemical composition of PM10 at (a) control and AAQ sites (unit: μg m^{-3}) and (b) curbside sites (unit: μg m^{-3})

(a)

Species	C1	C2	AAQ1	AAQ2	AAQ3	AAQ4	Detection limit
PM10	76	114	159	151	72	135	0.5
BSF	13.2	17.5	21.2	22.0	14.7	31.0	0.005
F	0.016	0.069	0.078	0.119	0.207	0.131	0.001
Cl	2.132	1.318	0.979	2.126	1.950	1.291	0.003
NO_3	0.689	0.691	1.071	0.522	0.284	0.624	0.002
SO_4	9.031	8.207	14.38	9.707	6.396	7.835	0.004
Na	2.535	3.054	3.675	2.810	1.971	2.050	0.015
K	1.512	2.240	3.637	3.265	1.183	1.205	0.045
Zn	2.754	0.001	2.348	0.680	1.638	3.113	0.001
Pb	0.130	0.365	0.232	0.054	0.051	0.004	0.004
Cd	0.004	0.001	0.009	0.002	0.001	0.001	0.001
Ni	0.032	0.006	0.056	0.076	0.015	0.003	0.003
Co	0.003	0.001	0.007	0.008	0.003	0.001	0.001
Mn	0.018	0.001	0.038	0.012	0.023	0.002	0.001
Fe	0.468	0.214	1.385	0.887	0.706	0.526	0.005
Cr	0.004	0.023	0.009	0.005	0.006	0.001	0.001
Al	0.843	0.001	0.720	0.539	0.456	0.001	0.001
Cu	0.022	0.002	0.042	0.024	0.016	0.002	0.002
Ba	0.925	0.259	0.173	0.476	0.232	1.166	0.001
Ag	0.001	0.023	0.051	0.104	0.001	0.080	0.001
B	1.688	0.001	0.742	6.521	0.588	2.257	0.001
Mg	0.005	0.005	0.039	0.043	0.009	0.025	0.005
V	1.028	0.001	0.257	0.556	0.087	0.213	0.001
Ca	0.609	0.001	1.159	2.991	0.469	1.169	0.001
Sr	0.008	0.001	0.023	0.014	0.002	0.006	0.001

(b)

Species	K1	K2	K3	K4	K5
PM10	126	193	157	134	318
BSF	20.5	21.0	21.0	34.5	84.3
F	0.084	0.110	0.074	0.091	0.146
Cl	1.022	1.145	1.814	1.121	1.727
NO_3	0.801	1.261	1.187	0.910	1.225
SO_4	10.23	11.78	9.844	11.06	13.82
Na	2.525	2.635	3.335	3.725	3.383
K	2.793	2.743	1.905	2.890	2.697
Zn	0.001	2.525	0.001	0.001	2.476
Pb	0.004	0.146	0.034	0.004	0.177
Cd	0.001	0.006	0.001	0.001	0.007
Ni	0.010	0.041	0.002	0.003	0.018
Co	0.063	0.012	0.002	0.002	0.029
Mn	0.099	0.034	0.014	0.006	0.053
Fe	5.154	1.468	0.895	0.466	3.136
Cr	0.014	0.007	0.001	0.001	0.011
Al	1.435	1.018	0.001	0.001	1.341
Cu	0.002	0.512	0.002	0.002	0.020
Ba	0.001	0.385	0.128	0.029	0.218

Table 2 continued

(b)

Species	K1	K2	K3	K4	K5
Ag	0.058	0.065	0.047	0.017	0.080
B	0.001	3.263	0.001	0.001	2.560
Mg	0.153	0.066	0.033	0.016	0.092
V	1.615	0.395	0.001	0.001	1.378
Ca	1.092	2.942	1.195	0.001	2.360
Sr	0.015	0.010	0.001	0.001	0.029

Table 3 (a) CMB performance indicators and (b) source apportionment of PM10 in Mumbai

(a)

Site	C1	C2	AAQ1	AAQ2	AAQ3	AAQ4	K1	K2	K3	K4	K5
R^2	0.87	0.9	0.88	0.85	0.93	0.87	0.89	0.84	0.92	0.96	0.83
χ^2	2.81	2.4	1.94	1.78	2.11	1.48	2.16	1.19	1.88	1.06	2.13
C/M	0.94	0.9	0.87	0.86	0.89	0.94	0.96	0.92	0.89	0.98	0.98
R/U	0.69	1.8	1.11	0.82	0.87	1.62	1.11	1.57	0.91	0.66	0.97

(b)

Source	Soil dust	Combustion	Marine	Industry	Vehicle	% explained
C1	8.3	–	13.2	50.5	10.8	82.8
C2	17.7	13.3	15	18.6	23	87.6
AAQ1	14.4	0.8	2.3	23.8	33.7	74.9
AAQ2	–	3.6	–	55.1	31.6	90.3
AAQ3	13.9	2.3	8.5	0.8	51.7	77.2
AAQ4	56.9	–	6.3	–	15	78.2
K1	11.3	13.5	33.8	1.5	15	75.2
K2	15	17.3	6.8	9	27	75
K3	38.9	0.8	4	–	34.9	78.6
K4	9	15.2	31.1	9.6	22.3	87.2
K5	10	20.6	3.6	2.1	36.3	72.5

PM10 concentration may be due to vehicular sources. Resuspension of road dust and industries may be the major contributors of PM10 as indicated by the high concentrations of Mn, Mg, Fe, Al, V and Co. The highest concentration of Cl and Na observed at Colaba and Chembur, respectively indicates the dominance of marine source at these sites. Nitrate and sulphate are higher at Metro and Vile Parle due to vehicular traffic. Comparing the site-wise species composition, the high concentration of Na, K, Cl is observed at all the sites apart from Ca at curbside, AAQ1 and AAQ2 and V at K1, K5 and C1, B at AAQ2, AAQ4, K2, K5 and C1; Al at K1, K2 and K5; Fe at K1, K2, K5 and AAQ1; Zn at AAQ4, K2, K5, C1, AAQ1, AAQ3. The higher concentration of SO_4 is observed as compared to NO_3 at all the sites. The average chemical composition of PM10 at all the 11 sites is given in Table 2a and 2b. With the available ambient air quality and source profile data for each species, the CMB modeling is carried out. Several trial and error exercises are performed in order to get the error statistics as per the specified guidelines. The performance of CMB results is evaluated by the performance indicators such as percentage mass explained by the model, the ratios as C/M and R/U, χ^2 statistic, *t*-statistic and R^2. The *t*-statistic value of >2 is observed for all the sites. The other statistics are given in Table 3a. It can be observed that R/U and C/M ratios lie within the acceptable range. R^2 is greater than 0.8 and χ^2 value is less than 4.

The percentage source contribution estimates are given in Table 3b. It can be observed that at control sites 'C1' and 'C2', industrial contributions prevail (50% and 19%, respectively). Although 'C1' is relatively cleaner than other sites, the role of meteorology can not be neglected. The

other significant contributions are from marine (13%) and vehicular (11%) activities. Due to the proximity to sea, the marine source contributes significantly to PM10 emissions. At 'C2', vehicular emissions contribute most to the PM10 (23%). The increasing number of vehicles and the meteorology may be the reason for high contribution of vehicular exhaust to PM10 emissions. At AAQ1 and AAQ3 sites, vehicular contributions are significant (34% and 32%, respectively), whereas at AAQ2, industrial contributions (55%) and at AAQ4, soil dust contributions (57%) are significant. Heavy traffic activities prevail at AAQ1 site, whereas AAQ3 is residential site with moderate traffic. The moderate contribution of vehicular emissions at AAQ is due to the heavy traffic as commercial area. The industrial contributions are due to meteorology. At curbside station K1, marine contributions are significant (34%), which is due to the proximity of the site to sea. This site is located on sea-side. Apart from the commercial activities, this area is residential also, with the four wheelers plying on the road. The vehicular and combustion process emissions therefore significantly contribute to PM10 at this site. At K2, vehicles are the most significant contributors of PM10 emissions (27%). The second most significant contribution at K2 and K4 is from combustion activities (17%) followed by soil dust emissions (15%). At K3, soil dust emissions contribute significantly to PM10 (39%) followed by vehicular emissions (35%). K2 and K3 sites are commercial in nature with heavy traffic activities. At K4, the marine emissions (31%) are significant followed by vehicular (22%) and combustion activities (15%). Although this site has the influence of industries, the impact may not be significant due to the fact that all the point source emissions are elevated providing ample dilution and dispersion. At K5, vehicular (36%) followed by combustion (20%) activities contribute most to PM10 emissions. Heavy traffic and the activities such as air port and bus depot prevail at this site. The study is useful for preparing the particulate matter reduction action plan for Mumbai, which can be extended further to other cities of India.

Acknowledgments The authors are thankful to the colleagues from Air Pollution Control Division of NEERI, Nagpur for their support to generate the data.

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