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Technical Information

First Measurements of Carbonaceous Aerosol across Urban, Rural and Residential Areas in Jeddah City, Saudi Arabia

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ABSTRACT Concentrations of black carbon (BC), organic carbon (OC), and total suspended particulate matter (TSP) were simultaneously assessed in urban, rural and residential areas in Jeddah city for one year from January to December 2017. It was aimed in the present study to provide information about the spatial and seasonal variability of these aerosol species in Jeddah, and insight into sources, processes and effects of meteorological conditions. To the best of our knowledge, this is the first study investigating the variability of carbonaceous aerosols (OC and BC) in Saudi Arabia. The average concentrations of OC, BC, and TSP varied spatially and temporally. The annual average concentrations of OC, BC, and TSP were 134.05, 7.16, and 569.41 μg m^{-3} and 34.32, 5.14, and 240.64 μg m^{-3} and 10.67, 4.39 and 101.31 μg m^{-3} in the urban, residential and rural areas, respectively. Moreover, there was a clear seasonal variation in the concentration of carbonaceous aerosols; the highest concentrations were recorded in February and September, while the lowest concentrations of OC were recorded during April, May and August in the urban, residential and rural sites, respectively. Nevertheless, the lowest concentrations of BC were recorded during March in the urban and residential sites and during November in the rural site. The relative concentrations of OC and BC to the TSP were relatively high, and they have a significant correlation with prevalent wind speed (−0.636, and −0.581 in the urban area), (−0.539 and −0.511 in the residential area), and (−0.508 and −0.501 in the rural area), respectively. The marked differences in the concentrations of BC and OC were reflected on OC/BC ratio, which is a good representative of different source types. This preliminary study showed that the potential local sources were emissions from traffic (fossil fuel), biomass burning, anthropogenic activities (e.g. car drifting and outdoor cooking), and industrial activities. The present study suggest the presence of highly inefficient combustion sources and highlight the need for the regulation of such emissions.

KEY WORDS Carbonaceous aerosols, Total suspended particulate matter, OC/BC ratio, Emissions, Jeddah

1. INTRODUCTION

The carbonaceous species in particulate matter (PM) constitute a massive fraction (about 40%) of the total PM and is highly related to related to regional and global climate change, visibility reductions, and adverse health effects in the atmo-

sphere (Lee *et al.*, 2020; Aswini *et al.*, 2018). They can classified as organic carbon (OC) and blackl carbon (BC) based on their thermal-optical properties (Mishra *et al.*, 2021; Lee *et al.*, 2020; Islam *et al.*, 2019; Kolhe *et al.*, 2018; Hema *et al.*, 2016; Xu *et al.*, 2015a, b; Angel *et al.*, 2014; Sandrini *et al.*, 2014).

Black carbon (BC) or soot is the carbonaceous aerosol produced either naturally or due to anthropogenic activities such as the incomplete combustion of the fossil fuels, bio-fuels and biomass, which are the primary and the most important (Sharma *et al.*, 2018), BC aerosols absorb solar radiation and play a great role in the global warming as well as regional climate impacts (Sharma *et al.*, 2018). Menon *et al.* (2002) stated that BC was responsible for the increasing flooding in India and drought in China as well as the reductions in the atmospheric transparency which caused about 20% reductions in agricultural productivity in India and China (cited in Sharma *et al.*, 2018; Chameides *et al.*, 1999). Moreover, BC alters the precipitation patterns and the earth's radiation balance (Watson, 2002). These adverse effects of BC aerosol depend strongly on its physical and chemical properties as well as on its residing time and distribution in the atmosphere (Jacobson, 2001). Scientific communities, especially in developing countries, are studying sources of BC, its physical and chemical properties and its detrimental impacts on nature for welfare of humans and ecosystems (El Sheekh and Hassan, 2021; Şahin *et al.*, 2020; Bertrand *et al.*, 2018; Angel *et al.*, 2014; Wolff, 2012).

OC is emitted directly into the atmosphere from traffic, the degradation of carbon-containing materials, industrial combustion, and biomass burning (Şahin *et al.*, 2020; Genga *et al.*, 2017; Hema *et al.*, 2016; Angel *et al.*, 2014). It effectively scatters light and may contribute significantly to visibility degradation (Basahi *et al.*, 2017). Polycyclic aromatic hydrocarbons (PAHs) are the main components of OC fraction, which are known to be carcinogenic (Haiba and Hassan, 2017; Harrison *et al.*, 2016a, b).

Measuring carbonaceous species (BC and OC) is important to understand the transport and transformation characteristics of air pollutants and their environmental effects (Panda *et al.*, 2016). BC and OC concentrations in the atmosphere are increasing with increasing coal and fossil fuel consumption (Bond *et al.*, 2014). Energy consumption, urbanization, and industrialization are proceeding rapidly in Saudi Arabia; these activities are the main sources for emissions of carbonaceous aerosols. Although BC and OC are important in atmospheric chemistry and atmospheric processing, information concerning their spatial and temporal variability is quite limited and fragmentary. Moreover, there is no such study in Saudi Arabia although of high concentration of PM due to rapid urbanization and industrialization. As a result, major traffic intersections in the city have turned to hot spots for air pollution from vehicular emissions (Basahi *et al.*, 2017; Harrison *et al.*, 2016a, b; Hassan *et al.*, 2013).

Earlier studies in Saudi Arabia were mainly focusing on spatial and temporal distribution of particulates and their organic and inorganic composition (e.g. Basahi *et al.*, 2017; Harrison *et al.*, 2016a, b; Hassan and Basahi, 2013).

To the best of our knowledge, there is no quantitative information concerning the spatial and temporal distributions of carbonaceous aerosols in Saudi Arabia, and their measurements are seriously lacking. Therefore, we carried out this investigation to quantify the spatial and temporal variability of BC, OC, and total suspended particulate matters (TSP) and their relationship to the prevailing meteorological conditions (wind speed, temperature and relative humidity) as well as the contributions of OC and BC to the total particulate mass to fill the abovementioned gap of knowledge. The comparison between OC, BC, and their ratios at different sites with different urbanization is particularly novel, especially in the arid regions and much needed in the field. The objective was to provide an OC/BC dataset for different urbanization areas to assess and understand the contribution of carbonaceous aerosols to the TSP for the first time in Saudi Arabia.

2. EXPERIEMNTAL

2.1 Study Area

Three monitoring locations (rural, urban and residential) were chosen along a transect of urbanization in Jeddah City, Saudi Arabia (N 21°67′, E 39°15′) to have a comprehensive study of the spatial distribution of carbonaceous aerosols. It has been described in our previous study (Fig. 1). Fig. 1 shows a map for Saudi Arabia and the selected areas in Jeddah. The urban area was characterized by dense traffic and heavy industries; the residential area was characterized by dense population, while the rural area was characterized by low population and

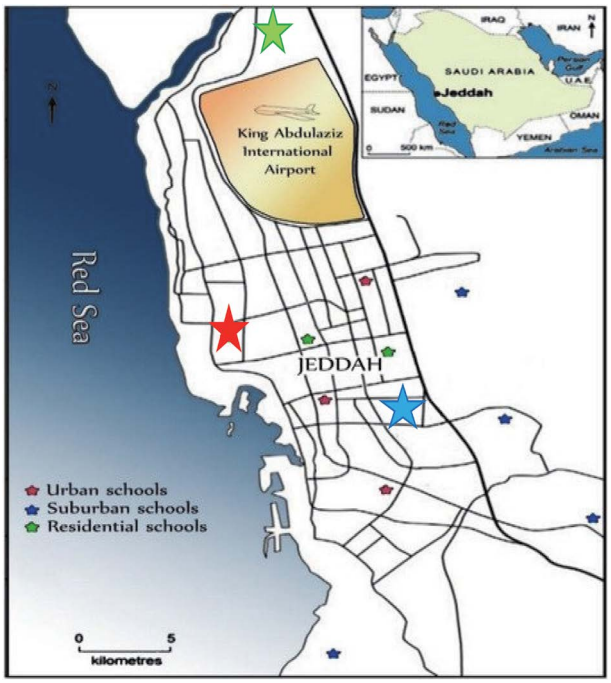

Fig. 1. Location of sampling sites in Jeddah, Saudi Arabia (red, blue and green stars represent the urban, residential and rural sites, respectively).

less intense traffic (Basahi *et al.*, 2017; Harrison *et al.*, 2016a, b).

The meteorological data (wind speed, wind direction, relative humidity and temperature) were obtained from the Saudi General Authority for Meteorology and Environmental Protection (www.pme.gov.sa). Fig. 3 shows wind speed, wind direction and monthly temperature during 2017 in Jeddah, Saudi Arabia.

2.2 Particulate Matter Sampling

Lear Siegler High Volume Air Samplers (70SCFM, Eco Environment, Australia) were used to collect total particulates on pre-weighed 47 mm Whatman sterilized quartz microfiber filters (QM/A, Whatman Inc., UK) at a flow rate of 1.1–1.4 $m^3 min^{-1}$ from the three sites simultaneously from January to December 2017 (12-h d^{-1}, starting at 08:00 GMT). Sampling was carried out for 12-h d^{-1} (8:00–20:00 Local time), due to security reasons, there was one sample daily for each site. The filters were conditioned and treated pre- and post-sampling. The filters were placed in desiccators during 48 h at stabilized conditions (25°C and 55% RH) prior to weighting. TSP mass concentrations were determined gravimetrically using an electronic microbalance (Mettler AJ150). Each filter was weighed before and after sampling, and the net mass was obtained by difference of two weights and expressed as $\mu g m^{-3}$ (Basahi *et al.*, 2017; Harrison *et al.*, 2016a, b; Sandrini *et al.*, 2014).

2.3 Quality Control/Quality Assurance

Calibration was employed to validate the determination of the TSP. Blank filters were examined for artifacts and to exclude any possible background contamination of OC and BC. Both OC and BC concentrations in field-filter blanks averaging 2.5 ± 0.18 $\mu g cm^{-2}$ ($n = 12$/site) were subtracted from that of the sample filters. Artifacts that resulted from the presence of gaseous OC or evaporation of some of the semi-volatile components of the particulate OC from the filters during sampling were avoided (Ramírez *et al.*, 2018; Salako *et al.*, 2012).

2.4 BC and OC Analysis

A portion of the filter was used to determine the BC and OC mass concentrations by means of a thermo-optical transmission method using a Sunset Laboratory OCEC Analyzer (RT-4, Sunset Laboratory Inc. Oregon, USA) following the EUSAAR2 thermal protocol (Titos *et al.*, 2017). Filters were heated, up to 800°C, to remove all organic carbon on the filter in a completely oxygen-free helium atmosphere (Samara *et al.*, 2014). As a result of oxidation, all carbon is converted to CO_2, which then is reduced by H_2 gas and turns into methane (CH_4). A complete chemical analysis was performed for all samples following the procedure of Samara *et al.* (2014). The generated CH_4 is detected by a flame ionization detector (FID) (Kuzu *et al.*, 2020; Aswini *et al.*, 2018; Satsangi *et al.*, 2012). The furnace is allowed to cool down to 550°C and a helium/oxygen (90%/10%) carrier gas mixture is used. With the second gradual increase in temperature, the elemental carbon in the filter is oxidized in the oxidation furnace. After this process, the analysis is completed by converting the elemental carbon into methane as inorganic carbon (Kuzu *et al.*, 2020). LOD was 0.15 $\mu g cm^{-2}$, and the uncertainty was better than 10% (the average analytical error was ± 1.7). The standard procedure for calibrating was conducted as recommended by Sunset Laboratory Inc.

2.5 Data Analyses

ANOVA test was applied to the data to test the differences of carbonaceous species in different sites using STATGRAPHICS statistical package (STAT 4, UK). A

linear regression analysis was used to evaluate the relationship between OC/BC ratios and BC, while the relationship between TSP, OC, BC, and different meteorological parameters were assessed using correlation analysis (Pearson Product Moment correlation coefficient), n = 12 (a monthly mean/site).

3. RESULTS AND DISCUSSION

3. 1 Concentrations of TSP

Monthly means of TSP, BC, OC, and OC/BC ratios are illustrated in Table 1 and Fig. 2. The TSP concentrations varied from 311.02 to 1908.8 μg m^{-3}, 58.23 to 189.1 μg m^{-3}, and 62.21 to 741.60 μg m^{-3} ± 89.27 μg m^{-3}, 240.64 ± 54.34 μg m^{-3}, and 101.31 ± 33.84 μg m^{-3} at the same sites, respectively (Fig. 3). The high concentrations at the rural and residential sites could be attributed to local emissions of biomass burning as well as long-range transport (Satsangi *et al.*, 2012).

The highest levels were recorded during February (1908.8 ± 289.19 μg m^{-3}, 284.6 ± 25.68 μg m^{-3}, and 158.7 ± 22.32 μg m^{-3}) and September (1096 ± 181.25 μg m^{-3}, 741.6 ± 77.27 μg m^{-3} and 189.18 ± 23.59 μg m^{-3}) for urban, residential, and rural sites, respectively (Table 1, Fig. 2). The high concentrations of TSP during February and September campaigns could be attributed to the heavy traffic, fire work, camping and burning of wood. These month are coincident with mid-year (February) and summer (September) vacations in Saudi Arabia. Furthermore, there were car drifting race during February and September nationwide. Moreover, these two months are the coldest ones in the year, so Saudi used to go out. Fig. 4 shows the wind speed direction as well as temperature in Jeddah during 2017.

Concentrations of TSP recorded in the present study are in agreement with our earlier results in Jeddah where the concentrations of TSP collected from residential and urban areas were 240 μg m^{-3} and 469 μg m^{-3}, respectively (Harrison *et al.*, 2016, 2014). Recently, Modaihsh and Mahjoub (2020) reported that the temporal variation observed for PM in Riyadh was associated mainly with the dust events. Moreover, Tawabini *et al.* (2017) found high concentrations of PM in Dhahran, Khobar, and Dammam, Saudi Arabia, and they ascribed these elevated concentrations to intensive industrial activities and congested roads. It is a worth mentioning that, our results are in agreement with the results of Satsangi *et al.* (2012), (Chen *et al.*, 2015), and (Shakya *et al.*, 2017),

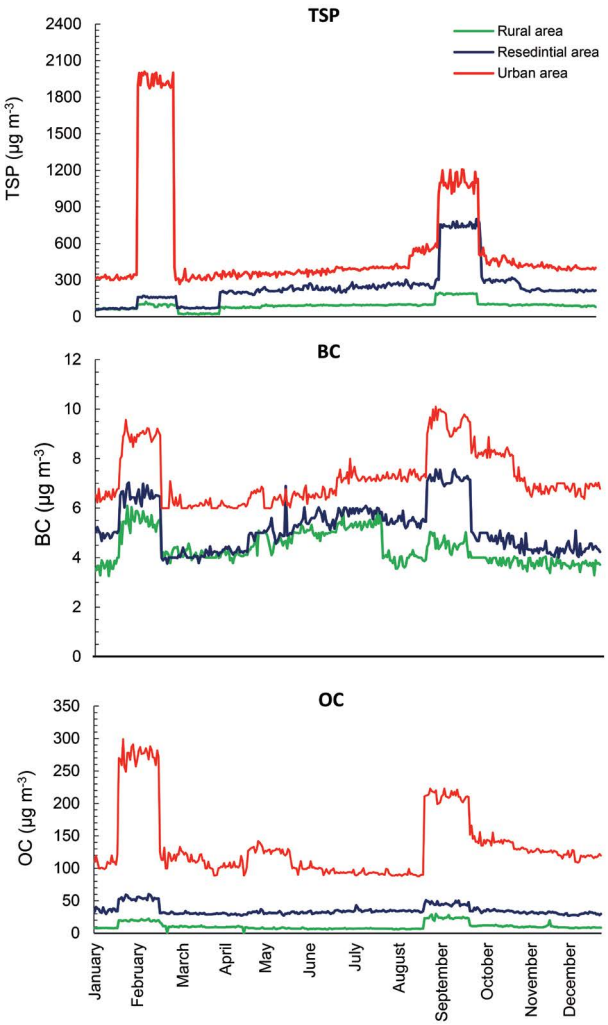

Fig. 2. Monthly concentrations of TSP, BC and OC at the three sites.

who found high concentrations of TSP (244.36 μg m^{-3}, 109.1 μg m^{-3}, and 229.7 μg m^{-3}) at urban, suburban and residential sites in Nepal, respectively. However, emission sources, weather conditions and other reasons, make the spatial distribution of pollutants between countries different.

The General Authority of Meteorology and Environmental Protection (GAMEP) in Saudi Arabia has assigned a 24 h annual average of 80 μg m^{-3} for 1 year and 240 μg m^{-3} for 8 hrs of TSP for residential, rural and other areas (www.pme.sa). Concentrations of TSP samples collected from the rural area and approximately 75% from those collected from the residential area were below the GAMEP standards (240 μg m^{-3}). On the other hand, all samples collected from an urban area fall above the pre-

Table 1. Monthly average of carbonaceous aerosols (OC, and BC) and TSP concentrations (μg m^{-3}) and OC/BC ratios for the sampling sites.

Month	Sampling site											
	Urban				Residential				Rural			
	OC	BC	OC/BC	TSP	OC	BC	OC/BC	TSP	OC	BC	OC/BC	TSP
January	101.10 ± 31.22	6.45 ± 3.45	15.67 ± 2.27	311.02 ± 111.25	33.56 ± 5.68	4.85 ± 2.11	6.92 ± 0.99	62.21 ± 9.23	7.98 ± 2.36	3.65 ± 0.67	2.68 ± 1.12	71.57 ± 7.27
February	269.80 ± 80.21	8.96 ± 4.36	30.12 ± 9.21	1908.8 ± 289.19	52.70 ± 9.62	6.45 ± 2.35	8.17 ± 2.19	158.7 ± 12.37	19.78 ± 4.12	5.45 ± 0.96	3.63 ± 0.98	158.7 ± 22.32
March	111.80 ± 29.18	6.12 ± 3.45	18.27 ± 6.92	311.3 ± 28.25	30.2 ± 6.78	4.02 ± 1.39	7.51 ± 2.37	69.51 ± 5.39	10.29 ± 2.34	4.11 ± 1.01	2.51 ± 0.67	58.23 ± 8.28
April	101.80 ± 33.39	6.13 ± 3.44	10.03 ± 3.21	436.6 ± 52.78	28.7 ± 4.24	4.21 ± 2.61	6.83 ± 1.12	198.2 ± 21.23	9.21 ± 1.58	4.12 ± 1.11	2.24 ± 0.92	73.67 ± 9.12
May	126.90 ± 38.19	6.35 ± 2.68	19.98 ± 3.47	353.6 ± 33.78	30.1 ± 7.03	4.95 ± 2.22	6.08 ± 1.57	210.1 ± 18.29	7.80 ± 1.29	4.58 ± 1.47	1.71 ± 0.67	89.6 ± 10.39
June	119.37 ± 43.46	6.47 ± 3.02	18.45 ± 2.19	361.2 ± 45.27	31.4 ± 8.37	5.4 ± 3.16	5.73 ± 2.01	218.4 ± 24.36	6.78 ± 0.96	5.01 ± 1.93	1.35 ± 057	92.21 ± 9.83
July	93.02 ± 27.10	7.15 ± 3.47	13.01 ± 1.28	388.9 ± 50.26	33.7 ± 7.78	5.8 ± 1.38	5.77 ± 2.34	245.5 ± 30.24	7.11 ± 1.04	5.32 ± 1.02	1.33 ± 038	95.45 ± 14.70
August	89.96 ± 19.28	7.22 ± 4.12	12.46 ± 2.11	401.41 ± 48.03	33.9 ± 6.37	5.45 ± 2.99	6.22 ± 2.37	264.6 ± 25.68	6.99 ± 1.11	3.92 ± 1.03	1.79 ± 072	99.19 ± 11.23
September	209.79 ± 34.47	9.48 ± 4.57	22.13 ± 1.93	109.6 ± 18.12	47.8 ± 9.18	7.14 ± 2.37	6.70 ± 0.67	741.6 ± 77.27	22.67 ± 4.68	4.58 ± 1.36	4.95 ± 1.21	189.18 ± 23.59
October	140.01 ± 27.37	8.12 ± 4.68	17.24 ± 1.57	460.5 ± 35.53	33.8 ± 2.38	4.86 ± 1.47	6.96 ± 2.03	293.8 ± 29.34	11.01 ± 2.31	3.89 ± 0.87	2.88 ± 1.09	100.2 ± 11.25
November	125.3 ± 44.57	6.69 ± 3.26	18.73 ± 4.32	414.4 ± 45.37	31.1 ± 4.78	4.25 ± 2.26	7.32 ± 1.29	211.6 ± 25.34	9.98 ± 1.37	3.68 ± 0.98	2.71 ± 0.37	98.78 ± 10.19
December	119.70 ± 38.29	6.78 ± 2.76	17.6 ± 2.19	389.2 ± 46.36	29.8 ± 6.11	4.23 ± 2.34	7.05 ± 2.93	213.5 ± 22.23	8.54 ± 2.03	3.71 ± 0.57	2.30 ± 0.63	88.89 ± 9.25
Sum of means "Σ"	1608.55 ± 329.36	85.92 ± 27.28	213.69 ± 33.28	6832.92 ± 45.65	411.86 ± 67.28	61.73 ± 7.37	81.26 ± 9.78	2887.72 ± 33.12	128.04 ± 22.38	52.02 ± 6.4	30.08 ± 6.56	1215.67 ± 135.34
Average of means "χ"	134.05 ± 43.27	7.16 ± 2.25	17.81 ± 3.26	569.41 ± 33.35	34.32 ± 7.26	5.14 ± 1.18	6.77 ± 2.45	240.64 ± 20.34	10.67 ± 2.38	4.34 ± 0.43	2.51 ± 1.06	101.31 ± 12.84
Carbonaceous aerosols/TSP	24.8% (± 4.23)				16.40% (± 2.11)				15.40% (± 1.98)			

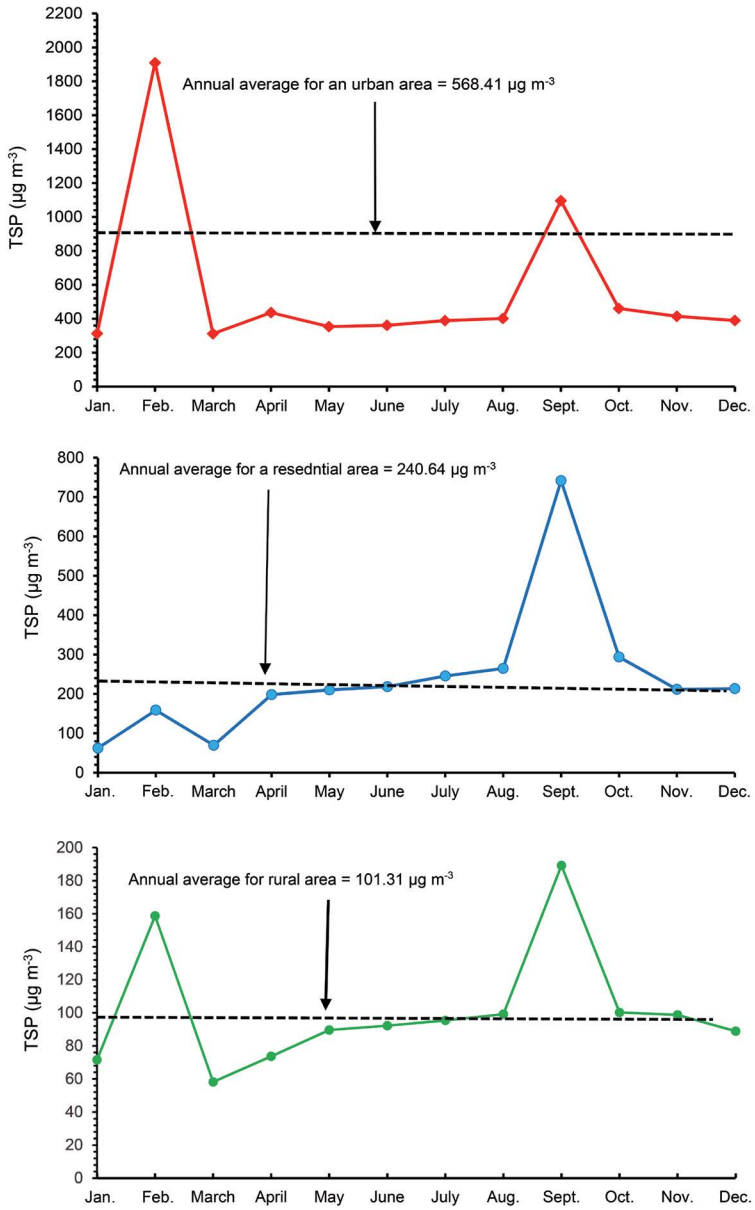

Fig. 3. Annual average concentrations of TSP in the studied areas.

scribed GAMEP standards (Fig. 3). Kumar *et al.* (2015) stated that developing megacities experience periods of air pollutions levels, which exceed international air quality standards. Although it is a global problem, some of the highest air pollution levels are found in rapidly expanding cities in India and China, Egypt, Iran, and Brazil. The sources, emissions, transformations and broad effects of meteorology on air pollution are reasonably well accounted in air quality control strategies in many developed cities; however these key factors remain poorly constrained in the growing cities of countries with emerging economies. These represent air pollution challenges, now and in the future.

3.2 Carbonaceous Aerosols

The OC and BC concentrations together with the OC/BC ratios are presented in Table 1. OC ranged from 98.96 ± 19.28 μg m^{-3} to 269.80 ± 80.21 μg m^{-3} with an annual average of 134.05 ± 43.27 μg m^{-3} in an urban site, while it ranged between 29.80 ± 6.11 μg m^{-3} to 52.70 ± 9.62 μg m^{-3} with an annual average of 34.32 ± 7.26 μg m^{-3}, and between 6.78 ± 0.96 μg m^{-3} to 22.67 ± 6.68

Fig. 4. Wind speed and wind direction during 2017 in Jeddah, Saudi Arabia.

$\mu g\,m^{-3}$ with an annual average of $10.62 \pm 2.38\ \mu g\,m^{-3}$ in the residential and rural sites, respectively.

BC ranged from $6.12 \pm 9.48\ \mu g\,m^{-3}$ to $9.48 \pm 4.15\ \mu g\,m^{-3}$, $4.02 \pm 1.39\ \mu g\,m^{-3}$ to $7.14 \pm 2.37\ \mu g\,m^{-3}$, and $3.65 \pm 0.67\ \mu g\,m^{-3}$ to $5.45 \pm 0.96\ \mu g\,m^{-3}$ with an annual average of $7.16 \pm 2.25\ \mu g\,m^{-3}$, $5.14 \pm 1.18\ \mu g\,m^{-3}$, and $4.34 \pm 0.43\ \mu g\,m^{-3}$ at urban, residential and rural sites, respectively (Table 1). Both BC and OC showed maximum concentrations during February and September.

Concentrations of OC were $269.80 \pm 80.21\ \mu g\,m^{-3}$, $52.70 \pm 9.62\ \mu g\,m^{-3}$, and $19.78 \pm 4.12\ \mu g\,m^{-3}$ in the urban, residential, and rural sites, respectively. The average concentrations of BC were $5.45\ \mu g\,m^{-3}$, $6.45\ \mu g\,m^{-3}$ and $8.96\ \mu g\,m^{-3}$ during February and $4.58\ \mu g\,m^{-3}$, $7.14\ \mu g\,m^{-3}$, and $9.48\ \mu g\,m^{-3}$ during September in the rural, residential, and urban sites, respectively. It was increased during February and September ($22.67\ \mu g\,m^{-3}$, $47.80\ \mu g\,m^{-3}$, and $209.79\ \mu g\,m^{-3}$) for the same sites, respectively (Table 1).

The OC and BC concentrations in the present study were compared with some megacities worldwide (Table 2); they were found to be higher than those recorded in other parts of the developed world. Concentrations of OC and BC were $4.2\ \mu g\,m^{-3}$ and $1.6\ \mu g\,m^{-3}$ in France, $6.3\ \mu g\,m^{-3}$ and $2\ \mu g\,m^{-3}$ in London, $4.8\ \mu g\,m^{-3}$ and $3.4\ \mu g\,m^{-3}$ in Birmingham (Seinfeld and Pankow, 2013) However, our results are comparable to those recorded in the developing countries. Concentrations of BC, and OC in Beijing were $36.7\ \mu g\,m^{-3}$ and $15.3\ \mu g\,m^{-3}$, and in Lahore were $47.7\ \mu g\,m^{-3}$ and $17.6\ \mu g\,m^{-3}$, respectively (Dan *et al.*, 2004; Smith *et al.*, 1996).

Moreover, Table 1 shows that the total contributions of carbonaceous species (BC + OC) to TSP in were 24.80, 16.40, and 15.40% for the urban, residential and rural areas, respectively. Organic carbon contributed more (23.54, 14.26, and 10.94%) than BC (1.26, 2.13, and 4.45%) to TSP mass for the same areas, respectively (Table 1). The elevated BC in the rural area suggests the presence of highly inefficient combustion (Şahin *et al.*, 2020; Angel *et al.*, 2014; Satsangi *et al.*, 2012).

The average rations of OC/BC were 2.44, 6.67, and 18.53 at the rural, residential and urban areas, respectively, this indicates significant site-to-sit variation (Fig. 5).

OC/BC does not affect atmospheric processing, and gives good indication about the source (Lee *et al.*, 2020). Novakov *et al.* (2009) stated that OC/BC ranging from 4.5 to 6.5 is for fossil fuel and above 8 is for biomass source, while OC/BC ratios, ranging from 1.5 to 2.5, are relatively constant and are generally unaffected by seasonality, sources, or technology changes (Titos *et al.*, 2017; Novakov *et al.*, 2009).

The OC/BC variation among the three sites site indicates the main sources of BC and OC are motor vehicles

Table 2. Mean OC and EC mass concentrations measured in some megacities of the world cited from the literature and observed in this study (μg m^{-3}).

Sampling site	OC	BC	OC/BC	Ref.
India (urban)	49.82	6.12	8.14	Ram and Sarin (2010)
India (urban)	30.96	3.78	8.19	Rengarajan *et al.* (2007)
India (residential)	26.88	3.44	7.76	Satsangi *et al.* (2012)
India (residential)	54.11	10.39	5.21	Tiwari *et al.* (2014)
India (Lahore)	47.7	17.6	2.67	Smith *et al.* (2006)
China (residential)	14.14	4.12	3.43	Li *et al.* (2016)
China (rural)	18.86	6.93	2.71	Zhao *et al.* (2013)
China (semi-urban)	31.99	11.08	2.84	He *et al.* (2004)
China (Beijing)	36.7	15.3	2.398	Dan *et al.* (2004)
Hong Kong	10.19	5.05	2.01	Ho *et al.* (2003)
Nepal (suburban)	27.2	3.46	7.86	Satsangi *et al.* (2012)
Nepal (residential)	–	15.3	–	Shakya *et al.* (2017)
India (semi-urban)	–	5.63	–	Joshi *et al.* (2015)
Athens (semi-urban)	25.7	8.2	3.13	Valaoras *et al.* (2000)
Paris (residential-rural)	14.6	5.9	3.47	Cachier *et al.* (1989)
London (rural)	3.01	1.43	2.11	DEFRA (2009)
Birmingham (UK)	4.8	3.4	1.41	Seinfeld and Pankow (2013)
Jeddah (urban)	134.05	7.16	18.72	Present study
Jeddah (residential)	34.32	5.14	6.77	Present study
Jeddah (rural)	10.67	4.34	2.46	Present study

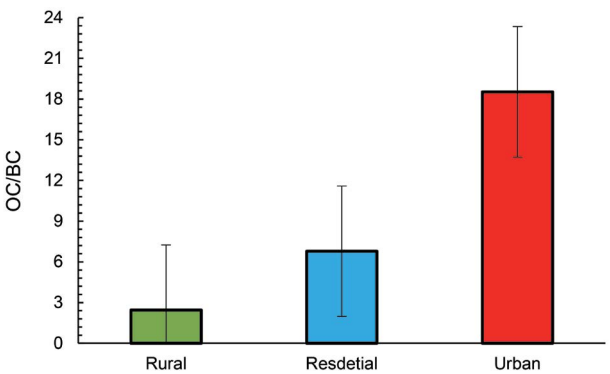

Fig. 5. Average OC/BC ratios for different sites in Jeddah (n = 12 + 1 SE).

emission and fossil fuel in the residential biomass burning in the urban site. The OC/BC ratios are known to be low in the rural site whereas high at the urban site (Shakya *et al.*, 2017, 2010). For example, OC/BC ratio in the urban site was highest and it reached 30.12 and 22.13 during February and September and the minimum was 10.03 which is higher than the highest ratio in residential and rural sites (8.17 and 4.95, respectively) (Table 1). This is in agreement with the results for urban areas around the world where this ratio ranged between 9 and 25 in Spain, Hungary, Italy, and Nepal (Shakaya *et al.*, 2017, 2010; Titos *et al.*, 2017; Sandrini *et al.*, 2014; Novakov *et al.*, 2009) (Table 2). Moreover, our results in good agreement with the results obtained for rural areas in London Paris and China (2.11, 2.47 and 3.43, respectively) and residential areas in India and China (ranged between 3.43 to 7.76) (Table 2). Moreover, Kim *et al.* (2010, 2009) reported high OC/BC in Korea (29.5). Our results indicate that there were seasonal variations as OC/BC ratio showed significant increases in winter, moreover, there were spatial variations among sites where the rural site had the lowest ratio (1.33–4.95), and the urban site had the highest ratio (10.03–30.12). Nevertheless, OC/BC in the residential area varied between 5.73 in June to 8.17 in February (Tables 1 and 2).

OC/BC ratios depend on emission sources and secondary organic aerosol (SOA) formation and they have spatial and temporal variations. Higher ratios in February and September suggest that there were secondary organic aerosol and an increased volatilization in the measurement sites. Our ratios, however, are similar to the values calculated from OC and BC emission inventories for developing countries, which give some confidence in our

Table 3a. Correlation matrix of TSP, OC, BC and different meteorological parameters at the urban area.

	TSP	OC	BC	Temp.	RH	Wind speed
TSP	–					
OC	**0.873**	–				
BC	**0.901**	**0.897**	–			
Temp.	**−0.711**	**−0.815**	**−0.652**	–		
RH	0.192	0.111	0.028	0.257	–	
Wind speed	**0.627**	**0.539**	**0.489**	−0.178	**−0.703**	–

Bold figures means significant at $p \leq 0.05$.

Table 3b. Correlation matrix of TSP, OC, BC and different meteorological parameters at the residential area.

	TSP	OC	BC	Temp.	RH	Wind speed
TSP	–					
OC	**0.716**	–				
BC	**0.628**	**0.792**	–			
Temp.	**−0.592**	**−0.638**	**−0.704**	–		
RH	0.218	0.018	0.119	0.210	–	
Wind speed	**0.501**	**0.499**	**0.467**	−0.107	**−0.663**	–

Bold figures means significant at $p \leq 0.05$.

Table 3c. Correlation matrix of TSP, OC, BC and different meteorological parameters at the rural area.

	TSP	OC	BC	Temp.	RH	Wind speed
TSP	–					
OC	**0.928**	–				
BC	**0.881**	**0.728**	–			
Temp.	**−0.839**	**−0.652**	**−0.579**	–		
RH	0.192	0.111	0.028	0.257	–	
Wind speed	**0.497**	**0.451**	**0.405**	−0.478	**−0.703**	–

Bold figures means significant at $p \leq 0.05$.

results and infer the climate effect of anthropogenic soot aerosols (Chhavi *et al.*, 2020). Our results highlighted the urgent need to control and regulate OC emissions in Jeddah.

A Pearson's correlation was executed in order to demonstrate the dependencies of various pollutants, it was formed with 3 different pollutants (TSP, OC and BC) and 3 different meteorological parameters. The meteorological parameters were wind speed, temperature (temp), and relative humidity (RH). The Pearson's correlation coefficients are shown in Table 3.

Pearson's coefficients showed that the highest correlation was between TSP, OC and BC concentrations, while the weakest correlation was with RH. Wind speed had the second highest correlation with TSP, OC, and BC. Its negative sign indicates that concentrations were decreased with the increasing wind speed. Similar trend was observed for the temperature. This suggests that air pollutant concentrations were increased in colder weather conditions (Kuzu *et al.*, 2020). These results are supported with the finding of Şahin *et al.* (2020), who reported that the dispersion and the concentrations of TSP, OC, and BC, strongly, depend on, and vary with, the wind speed and direction.

Table 3 shows the relationship between TSP, OC, BC and meteorological parameters (temperature, relative humidity and wind speed). Temperature was negatively correlated with TSP ($r = -0.711$, -0.592, and -0.839), OC ($r = -0.815$, -0.638 and -0.652) and BC ($r = -0.652$, -0.704, and -0.579) at urban, residential and

rural sites, respectively; indicating the profound role of low temperature in increasing concentration of carbonaceous aerosols (Kuzu *et al.*, 2020; Islam *et al.*, 2019; Satsangi *et al.*, 2014; Begum *et al.*, 2012). Similarly, there was negative significant ($p < 0.05$) correlation between wind speed and TSP ($r = -0.627$, -0.501 and -0.597), at urban and residential sites, respectively (Table 1), Moreover, there was negative significant correlation between wind speed and OC ($r = -0.636$, -0.539 and -0.508) at the urban, residential and rural sites, respectively). Similarly, BC was negatively correlated with BC (-0.5981, -0.511 and -0.501, for the same sites, respectively) (Table 3). These results indicate that wind speed is not the sole controlling factor for the apparent correlation (Panda *et al.*, 2016). Tai *et al.* (2012) in the USA, Angel *et al.* (2014) in the Philippines and Panda *et al.* (2016) in India found similar results and they explained the correlation as a result of pollutants accumulation which led to an increase in levels of TSP. They attributed the accumulation of these pollutants to the wind circulation pattern across and lower wind speed. Moreover, Table 3 shows that both BC and OC values were well correlated for all sites ($r = 0.897$, 0.792, and 0.728 for an urban, a residential, and a rural site, respectively), suggesting that the BC and OC in Jeddah may be emitted from the same sources, which are in agreement with the results of Sung *et al.* (2013) in South Korea.

Fig. 6 shows the linear regression of apparent OC/BC ratios on BC concentrations at the three sites. An intercorrelation pattern was evidenced at the urban and rural sites. There was a good overall fit for the linear regression model between OC/BC and BC data obtained in the urban ($p < 0.001$; $R^2 = 0.635$) and the rural ($p < 0.01$, $R^2 = 0.505$) sites, respectively (Fig. 6). Chen *et al.* (2014) found a strong correlation between BC and OC in China and they assumed that they were emitted from the same source. The dominant sources of BC are local because its concentration depends on the wind direction. Consequently, the OC/BC ratio is then attributed to local emissions: traffic, biomass burning, or brick kilns (Chen *et al.*, 2014). Recently, Ni *et al.* (2019) investigated the sources and formation mechanisms of carbonaceous aerosols in China. They found that strong correlation between wind and aersols is a good indication of local sources, moreover, good correlation between OC and BC is a good indication that they are emitted from the same source(s). The strong correlation at these sites could indicate that carbonaceous aerosols could possibly

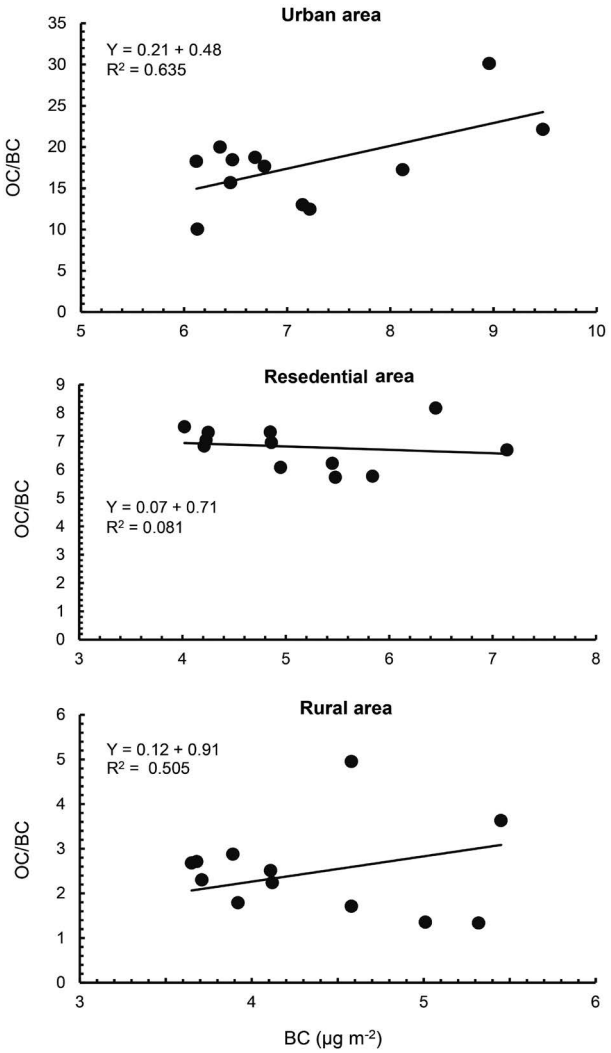

Fig. 6. Linear regression of apparent OC/BC ratios on BC concentrations at the three sites.

be emitted directly from primary sources, with some of the primary sources being fugitive emissions from combustion and leakage during coal charging and coke pushing. On the other hand, OC/BC and BC were uncorrelated ($p > 0.05$, $R^2 = 0.0.081$) in the residential site. Chen *et al.* (2014) found similar results and they attributed this poor correlation to gas- and solid-phase redistribution of semi-VOCs.

It is worth investigating organic and black carbon as well as elemental carbon in fine particles (PM_{10}, $PM_{2.5}$) in the future for a better understanding of the source identification and unidentified components of the PM because they are more enriched in the fine mode (Ni *et al.*, 2019; Kolhe *et al.*, 2018; Na and Cocker, 2009).

4. CONCLUSIONS

The data collected for a period of one year (January–December 2017) were analyzed to interpret the monthly, seasonal and spatial variation of carbonaceous aerosols and TSP in urban (traffic influenced), residential, and rural sites in Jeddah for the first time. An attempt has also been made to analyze the effects of meteorological parameters like wind speed, wind direction and rain together with local events for their variation. Increased vehicular movement, car drifting and cooking activities including substantial burning of wood and other biomass in February and September contributed to higher c of BC concentrations of TSP and carbonaceous aerosols. When vehicular movement and cooking activities were reduced during other months, there came a decrease in their emission. In addition, the wind speed contributes for the variation in their concentrations.

The OC mass at an urban site, during the sampling period (January–December 2017), was found to be about 4 and 13 times higher than at the residential or rural sites, respectively, albeit the similar BC annual cycle at three the sites. This is associated with the different nature of anthropogenic activities rather than local meteorology at these sampling sites. Monthly average BC and OC concentrations were higher than the concentrations reported for urban environments in other parts of the world, this could be ascribed to the arid environment in Saudi Arabia. The concentrations of OC and BC relative to the TSP are also high and have a good correlation with wind speed. Based on these relationships, we concluded that the dominant sources of carbonaceous aerosols at this site are local (traffic, coal, and biomass burning) rather than regional. Local events like festivals, camping, car drifting and outdoor cooking directly influence the concentration of carbonaceous aerosols.

There were hardly any data in Saudi Arabia on the contribution of carbon to PM. The present study represents the first preliminary investigation to fill this knowledge gap. Moreover, it is hoped that our study can provide important first-hand data for the future development of PM and OC inventories in the region. The reduced estimate for OC/BC in aerosols strengthens the argument that reduction of soot emissions maybe a useful approach to slow global warming. Furthermore, the present study highlights the impact of carbonaceous aerosols on human health and climate change in Saudi Arabia. It is hoped that such studies would help for a better understanding of the ongoing climate change scenario in an arid region of the world.

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