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Article

Characteristics and Seasonal Variations of Carbonaceous Species in $PM_{2.5}$ in Taiyuan, China

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Abstract: Seasonal characteristics of $PM_{2.5}$, organic carbon (OC) and elemental carbon (EC) were studied in Taiyuan from 2009 to 2010. $PM_{2.5}$ samples were collected by pre-baked quartz filters with high-volume air sampler, and then OC and EC were analyzed by thermal/optical reflectance method. The annual average concentrations of $PM_{2.5}$, OC and EC were 220.2, 37.4 and 19.6 μg/m^3 respectively, which were higher than those in most regions in China. Total carbonaceous aerosol (TCA) accounted for more than one third of the total $PM_{2.5}$ mass. The levels of $PM_{2.5}$, OC and EC were the highest in winter, followed by spring, fall and summer. OC and EC were well correlated in summer compared with other seasons, indicating the presence of other additional sources such as biomass burning in fall, coal combustion for heating in winter and dust in spring. Higher OC/EC ratios in winter might be primarily attributed to the significant increase of direct emission of OC as a result of coal and biomass combustion, and also cooling effect of carbonaceous aerosols due to low temperature and stagnated atmospheric condition. These results showed that the pollution of carbonaceous particles in Taiyuan was serious, and might be an inducing factor of dust haze, especially in winter.

Keywords: $PM_{2.5}$; organic carbon (OC); elemental carbon (EC); second organic carbon (SOC); Taiyuan

1. Introduction

In recent years, carbonaceous aerosol as a major component of atmospheric fine particles has caused wide concern due to its many adverse effects on human health, haze, hydrological cycle and climate change. Carbonaceous species are generally classified into elemental carbon (EC, also called black carbon or soot) and organic carbon (OC). EC is released directly from the incomplete combustion of carbon-contained materials (*i.e.*, coal, diesel, gasoline and biomass). As the second most important component of global warming after CO_2, EC can reduce the optical depth and visibility by light absorption and also affect the crop yield by reducing solar radiation. OC can be either released directly from combustion sources (primary organic carbon, POC) such as vehicular exhaust, fossil fuel combustion, biomass burning and cooking [1–4], or formed through atmospheric oxidation of reactive organic gases followed by gas-to-particle conversion processes (secondary organic carbon, SOC)involving various physical, chemical and biological processes of extreme complexity, and being controlled by a number of factors such as temperature, sunlight intensity and O_3 concentration [2,4]. OC can change the global climate by significantly affecting the surface tension of cloud droplets [2,5]. Also, OC usually contains hundreds of organic compounds, some of which are mutagenic and/or carcinogenic, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) as well as polychlorinated dioxins and furans (PCDD/Fs), posing a risk to human health. Therefore, it is important to understand the characteristics of carbonaceous species in particulate matters in urban atmosphere [6,7].

In different places, carbonaceous species have different contributions to the total fine particle mass from 20% up to 80%. Offenberg and Baker found that the OC and EC primarily existed in fine particles in urban Chicago atmosphere during summer and winter conditions [8]; Samara *et al.* found that more than 80% of OC and EC at both urban-traffic site and urban-background site in northern Greece appeared to be distributed in the $PM_{2.5}$ fraction, particularly in the cold season [9]. Several studies on carbonaceous species in $PM_{2.5}$ and/or PM_{10} were also reported in Chinese cities, like Beijing, Shanghai, *etc.* It has been estimated that carbonaceous species contributed 20%–50% to the total mass of fine particles in urban atmosphere from small-scale to regional-scale atmosphere [4,10,11]. OC levels were always higher than EC at all sampling sites, and carbon concentrations were higher in some inland cities (such as Xi'an, Chongqing, Wuhan and Changchun) than those in coastal cities (such as Hong Kong, Xiamen and Qingdao). The concentrations of carbon matter were generally higher in winter than other seasons as a result of the increased coal combustion for heating and the stable atmospheric conditions at lower air temperature.

Taiyuan, the capital of Shanxi Province, is one of the most heavily polluted cities in the world, with large coal consumption for energy production and many industrial activities including electricity, coke, steel and chemical products, and unfavorable dispersion condition of hills on three sides and a marked continental monsoonal climate [12,13]. Combined with strong administrative action and improvement of the pollution control technologies, the SO_2 and PM_{10} concentrations decreased steadily, but still

exceed the second threshold of China National Ambient Air quality Standard (NAAQS) [14]. Carbonaceous species are the major components of fine particles during winter in Taiyuan, and coal combustion is the main source for OC and EC in "heating season". Few studies have reported the seasonal distribution of carbonaceous species in particulate matters, especially in fine particles in Taiyuan. The objectives of this paper are to investigate the seasonal characteristics of $PM_{2.5}$, OC and EC, and estimate the SOC contributions to total carbonaceous loading.

2. Experimental Section

2.1. Site Description

With a population of 4.2 million and a land area of about 1500 km^2, Taiyuan was reported to consume about 70.0 million tons of coal per year in Taiyuan, about 37.0% of which was used as fuel for power, industrial boiler and residential purposes. The terrain of Taiyuan is like a dustpan surrounded by mountains in west, north and east directions, but with a valley plain in the south. Located in the continental interior and far away from the coast, Taiyuan belongs to the warm temperate zone with continental monsoon climate. The annual average temperature in Taiyuan is 9.5 °C, with the lowest value in December and January (daily average, −6.8 °C) and the highest in June and July (daily average, 23.5 °C).

As shown on the map, sites 1 and 4 are the power plants for electricity and heating supply, while sites 2 and 3 are the iron and steel production and heavy machinery industries, all of which represent more than a half of coal combustion and pollutant emission sources. Based on the data from eight atmospheric environmental monitoring stations in Taiyuan, there was no difference between four central stations along with the main east-west central street-Yingze Street, which implicated that air pollutants dispersed steadily in the whole downtown area [15]. The sampling site was located on the roof of a 15-story office building at the northwest of Yingze Bridge, which was in the downtown and the most populated area in Taiyuan (Figure 1).

2.2. Sampling

The 24-h $PM_{2.5}$ samples were collected on the quartz fiber filters (QFF, Whatman Ltd., 8 × 10 inch) using a high-volume $PM_{2.5}$ air sampler (TH-1500, Tianhong, China) in summer (1–21 August 2009), fall (29 September–27 October 2009), winter (24 November–9 December 2009 and 4–10 January 2010) and spring (27–31 March 2010, 2–18 April 2010), operating at a flow rate of 1.05 m^3/min. The sampler was checked and calibrated by a flow calibrator carefully before using. During the sampling periods, meteorological data, including ambient temperature, relative humidity (RH), wind speed, wind direction, and rainfall were recorded by a weather instrument (Qingsheng JL-03 weather instrument, China).

All QFF were pre-baked at 450 °C for 4 h before sampling to remove residual carbonaceous contamination. Before and after sampling, all QFF were weighed by electronic microbalance (±1 μg sensitivity, AB204-S, METTLER TOLEDO, Greifensee, Switzerland) under constant temperature (25 °C) and relative humidity (50%) in a constant climate chamber (BE-TH-1400M8, Dongguan, China) for 24 h. After weighting, the QFFs were sealed and stored in a freezer at −10 °C for further analysis.

The mass concentrations were calculated as the disparity weight of each filter before and after sampling divided by the sampling volume.

2.3. Carbonaceous Analysis

Carbonaceous species were analyzed by a DRI Model 2001A thermal/optical carbon analyzer (Atmoslytic Inc., Calabasas, CA, USA). According to the IMPROVE-A thermal/optical reflectance (TOR) protocol, the instrument performed the sample to 140 °C (OC1), 280 °C (OC2), 480 °C (OC3) and 580 °C (OC4) in a non-oxidizing helium (He) atmosphere, and 580 °C (EC1), 740 °C (EC2) and 840 °C (EC3) in 2% O_2/98% He atmosphere [1,5]. The carbon evolved at each temperature was oxidized to CO_2 and then reduced to CH_4 for quantification with flame ionization detector. Some of the organic carbon was pyrolized to BC with the increase of temperature in the inert He and resulted in darkening of the filter deposit which was monitored by reflectance of 633 nm light of He-Ne laser. After adding O_2, the original and pyrolized BC combusts and the reflectance increased. The amount of carbon was measured after adding O_2 until the reflectance achieved its original value termed as optically detected pyrolized carbon (OPC). The IMPROVE protocol defined OC as OC1 +OC2 + OC3 + OC4 + OPC and EC as EC1 + EC2 + EC3 − OPC. The analyzer was calibrated using filter blank and known quantities of CH_4 every day. Replicate analyses were performed on every group with 10 samples. The differences indicated by replicate analyses were smaller than 10% for OC and EC.

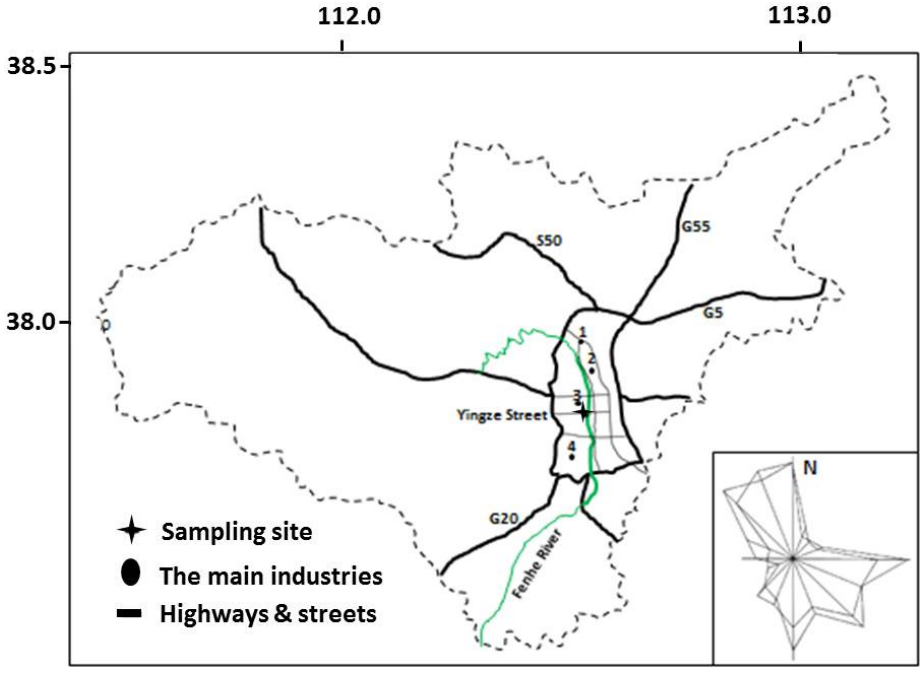

Figure 1. Sampling site and some important PM emission sources.

3. Results and Discussion

3.1. $PM_{2.5}$ Level

As shown in Figure 2, the daily average $PM_{2.5}$ concentrations ranged from 83.4 to 477.9 μg/m^3, exceeding the Grade II standard value on daily concentration of $PM_{2.5}$ (75 μg/m^3) according to

China National Ambient Air quality Standard (NAAQS)(GB3095-2012) in all of the sampling days except 2 August 2009. The annual average concentration of $PM_{2.5}$ was 220.2 ± 98.5 μg/m^3, which was 6.3 times of the Grade II standard value on annual average concentration of $PM_{2.5}$ (35 μg/m^3) according to NAAQS. Meanwhile, $PM_{2.5}$ levels in Taiyuan largely exceeded the 24-h and 1-year guidelines of WHO air quality standard [6]. In comparison with other cities in China, $PM_{2.5}$ annual concentration in Taiyuan was higher than that in the PRDR (Pearl River Delta Region, 102.7–129.9 μg/m^3 [16]), Beijing (115.0–127.0 μg/m^3 [17]) and Shanghai (~60 μg/m^3 [18]).

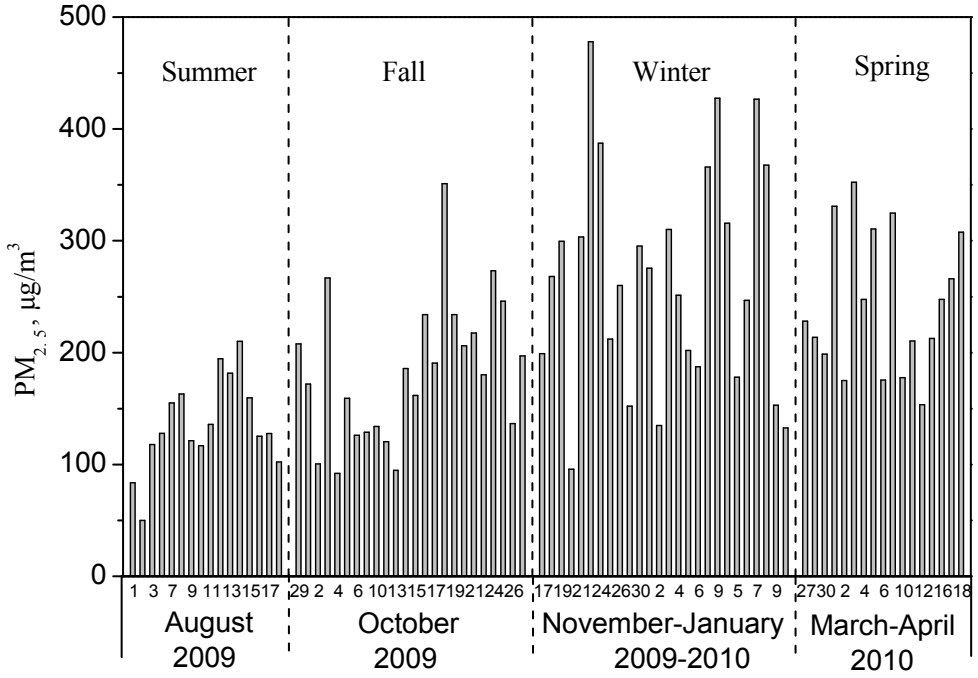

Figure 2. $PM_{2.5}$ levels in different seasons in Taiyuan.

For different seasons, the highest $PM_{2.5}$ level was found in winter (95.9–477.9 μg/m^3 with an average of 260.8 ± 113.6 μg/m^3), followed by spring (153.4 to 352.3 μg/m^3 with an average of 248.7 ± 89.6 μg/m^3), and the lowest was in summer with an average concentration of 135.8 ± 40.9 μg/m^3. The $PM_{2.5}$ seasonal trend in Taiyuan was consistent with those reported in other cities in China like Beijing, *etc.* (Table 1), which can be mainly explained as the impact of both local emissions and climate conditions (Figure 3). Winter is a "heating season", lasting from November until the following March. Local emissions increased rapidly, but the terrain of dustpan and atmospheric inversion prevented the dispersion of air pollutants. In spring, the lower relative humidity (RH %) and higher wind speed caused re-suspension and blowing of particle matter, which led to higher $PM_{2.5}$ level. In summer, the lowest concentration of $PM_{2.5}$ may be due to enhanced thermal convection and more rainfall than other seasons. Figure 4 showed the 48-h back trajectories of air mass during the sampling period in summer and winter in Taiyuan by HYSPLIT_4, and the pathways of air mass from northwest in winter and southeast in summer were accounted for more than 80.0% and 60.0% in the total pathways, respectively. Except for local emissions, long-range atmosphere transport (LRAT) processes may also influence the $PM_{2.5}$ level in Taiyuan, which was associated with the predominant wind direction mainly from the northwest in winter and southeast in summer [19].

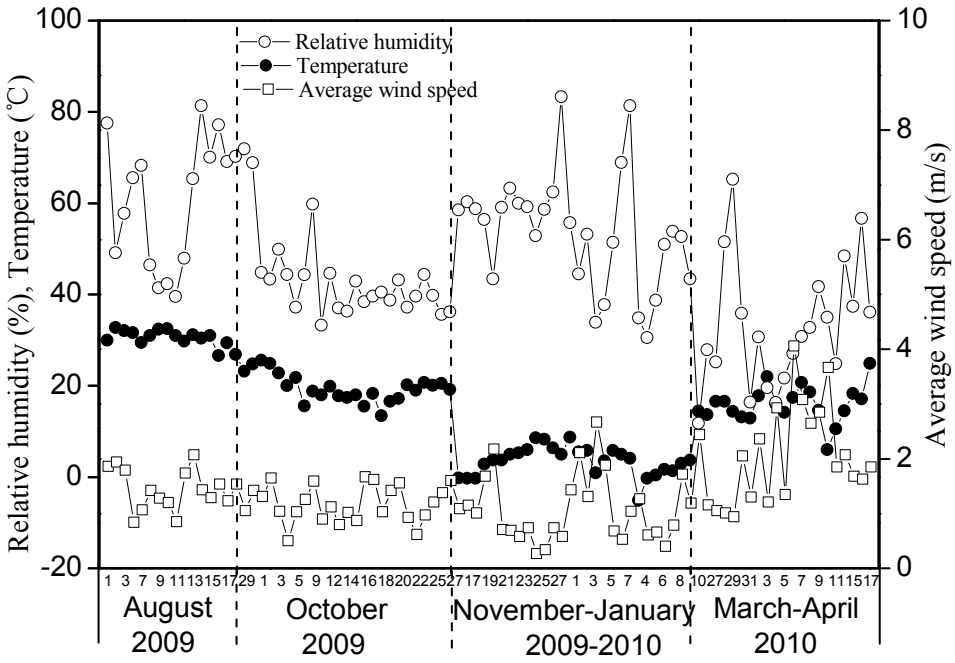

Figure 3. The meteorological parameters in the sampling periods in Taiyuan (Summer: August 2009; Fall: September–October 2009; Winter: November 2009–January 2010; Spring: March–April 2010).

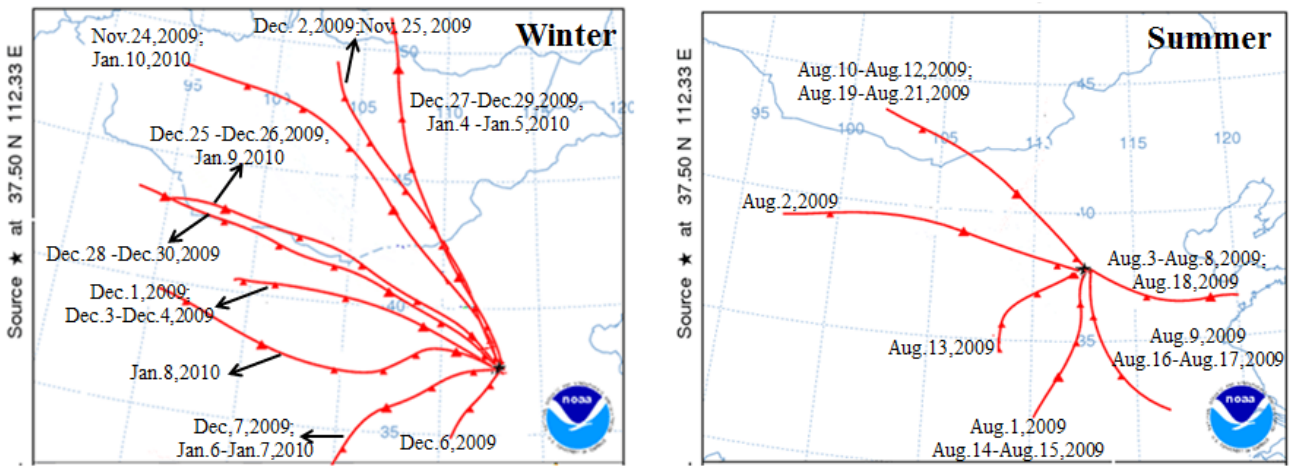

Figure 4. The 48-h back trajectories of air mass during the sampling period in summer and winter in Taiyuan.

3.2. Carbonaceous Species in $PM_{2.5}$

Table 1 listed the average concentrations of OC and EC in $PM_{2.5}$ in different seasons in Taiyuan and other cities in China, and Figure 5 presented the daily values during the sampling period. The daily concentrations of OC in summer, fall, winter and spring were 7.6–22.4 μg/m^3, 10.2–44.0 μg/m^3, 31.5–125.8 μg/m^3, and 17.3–42.4 μg/m^3, with an average of 13.2 ± 4.3 μg/m^3, 25.7 ± 8.3 μg/m^3, 62.7 ± 27.7 μg/m^3 and 31.6 ± 8.7 μg/m^3, respectively, while the daily concentrations of EC were 1.9–15.7 μg/m^3, 5.0–31.9 μg/m^3, 9.4–41.7 μg/m^3, and 9.7–27.4 μg/m^3, with an average of 8.8 ± 4.1 μg/m^3, 16.3 ± 6.9 μg/m^3, 25.4 ± 8.5 μg/m^3, and 21.6 ± 7.9 μg/m^3, respectively. Obviously, the concentrations

of OC were higher than those of EC in all observed days, especially in winter days (Figure 5), which was consistent with the result of 14 cities over China reported by Cao *et al.* [11]. With an annual average of OC being 37.4 μg/m^3 and EC 19.6 μg/m^3, the OC and EC levels in Taiyuan ranked the highest in China among other cities measured by TOR method [1,2,10,18].

Table 1. Average concentrations of $PM_{2.5}$, organic carbon (OC), elemental carbon (EC) and their OC/EC ratios in Taiyuan and other cities in China.

City	Season (Period)	$PM_{2.5}$ (μg/m^3)	OC (μg/m^3)	EC (μg/m^3)	OC/EC	Reference
Taiyuan	Summer (August 2009)	135.8 ± 40.9	13.2 ± 4.3	8.8 ± 4.1	1.7 ± 0.7	**This study**
	Fall (September–October 2009)	182.2 ± 63.1	25.7 ± 8.3	16.3 ± 6.9	1.8 ± 0.9	
	Winter (November 2009–January 2010)	260.8 ± 113.6	62.7 ± 27.7	25.4 ± 8.5	2.5 ± 0.6	
	Spring (March–April 2010)	248.7 ± 89.6	31.6 ± 8.7	21.6 ± 7.9	1.5 ± 0.3	
Hong Kong	Summer (June–July 2002)	31.0 ± 16.9	5.3 ± 2.1	3.2 ± 2.6	1.9	[1,10]
	Winter (January–February 2002)	54.5 ± 22.9	9.6 ± 4.5	4.7 ± 2.9	2.3	
Guangzhou		78.1 ± 29.7	15.8 ± 6.4	5.9 ± 2.1	2.7	
		105.9 ± 71.4	22.6 ± 18.0	8.3 ± 5.6	2.7	
Shenzhen		47.1 ± 16.7	7.6 ± 4.9	4.2 ± 3.1	1.8	
		60.8 ± 18.0	13.2 ± 4.1	6.1 ± 1.8	2.2	
Zhuhai		31.0 ± 20.0	5.4 ± 3.4	1.9 ± 0.9	2.9	
		19.3 ± 23.7	12.2 ± 4.4	5.0 ± 1.6	2.5	
Xi'an	Fall (September–October 2003)	—[a]	34.1 ± 18.0	11.3 ± 6.9	3.3	[18]
	Winter (November 2003–February 2004)	—	61.9 ± 33.2	12.3 ± 5.3	5.1	
Beijing	Winter (January–February 2001)	184.5 ± 33.9	40.1 ± 4.4	9.9 ± 3.0	4.3	[3]
	Spring (March 2001)	118.5 ± 27.3	21.5 ± 7.3	6.5 ± 0.1	3.3	
	Summer (June–July 2001)	94.4 ± 15.6	17.1 ± 2.3	8.0 ± 1.6	2.1	
	Fall (September–October 2001)	92.2 ± 18.5	21.0 ± 2.3	10.7 ± 1.8	2.0	
14 cities [b]	Winter (January 2003)	163.9	38.1	9.9	3.8	[11]
	Summer (June–July 2003)	71.2	13.8	3.6	4.2	

[a] "—" represent no data; [b] Average concentration of $PM_{2.5}$, OC, EC and their ratios in 14 cities including 7 cities in Northern China (Beijing, Changchun, Jinchang, Qingdao, Tianjin, Xi'an and Yulin) and 7 cities in Southern China (Chongqing, Guangzhou, Hong Kong, Hangzhou, Shanghai, Wuhan and Xiamen).

For seasonal variation, both OC and EC in this study strongly varied as following order: winter > spring > fall > summer. The seasonal trends of OC and EC levels were consistent with the $PM_{2.5}$ variation trend, which was attributed to that OC and EC were mainly enriched in fine particles especially in $PM_{2.5}$ [8]. The OC and EC levels in winter were 4.8 and 2.9 times of those in summer, respectively, and consistent with higher concentrations of OC and EC in winter than in summer in other Chinese cities summarized in Table 1. It may be due to more coal combustion for heating in winter, which is the main energy consumption in Taiyuan [20,21]. Comparing OC and EC in different seasons with those in other studies (Table 1), this study showed that the concentrations of EC in all seasons were higher than those in corresponding seasons in all other cities, while the concentrations of OC in four seasons were either comparable with or higher than those in corresponding seasons in most cities.

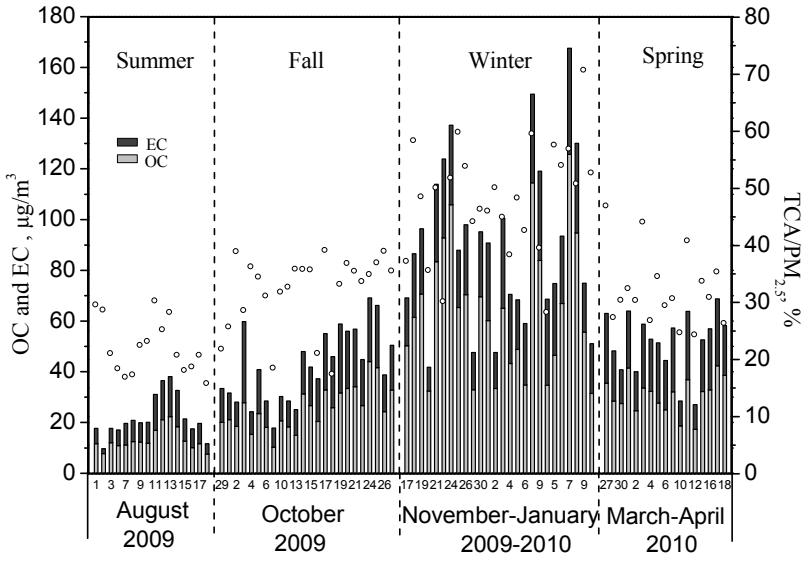

Figure 5. Carbonaceous species in $PM_{2.5}$ in Taiyuan (total carbonaceous aerosol (TCA) = 1.6 × OC + EC).

The total carbonaceous aerosol (TCA) can be calculated by the sum of EC and OM, which is estimated by multiplying the amount of OC by 1.6 [22]. As shown in Figure 3, the contributions of TCA to the $PM_{2.5}$ mass in different seasons were winter (28.3%–70.8%) > spring (24.4%–47.0%) > fall (17.5%–39.2%) > summer (15.9%–30.3%), which was consistent with the seasonal variations of OC and EC. TCA contributed more than one-third of the $PM_{2.5}$ mass in Taiyuan, which was similar to the results in PRDR regions reported by Cao *et al.* [1,10].

3.3. Relationship between OC and EC

Figure 6 shows the regression between OC and EC concentrations in the four seasons, which can give some indication of the origin of carbonaceous particles. Strong correlation ($R^2 = 0.907$) between OC and EC in summer indicated they were emitted from similar sources (e.g., commercial coal combustion and vehicular exhaust) and underwent a similar atmospheric dispersion process. The relatively poor correlations between OC and EC in fall, winter and spring ($R^2 = 0.422$–0.596) indicated that other additional sources such as biomass burning after harvest in fall, biomass burning and coal combustion for heating in winter and dust in spring were present. OC and EC were well correlated in summer than in winter in Hong Kong, Xiamen, Changchun and Xi'an, compared with other 10 cities in their study by Cao *et al.* [11]. In the regression between OC and EC (OC = *a*EC + *b*, Figure 6), the *a*EC represents the primary OC associated with combustion sources. Higher *a* value (2.60) in winter indicated the large contribution to carbonaceous aerosol from primary emissions, whereas the low *a* value for summer, fall and spring (0.68–1.01) was attributed to the contribution of SOA.

The OC/EC ratio was often used as a tracer for changes in emission sources and transformation characteristics of carbonaceous aerosol. The daily OC/EC ratios in all seasons fell between 1.0 and 4.0 (except October 1 and 3, 2009, Figure 7), which was similar to most urban sites around the world [1]. This result indicated OC and EC in Taiyuan were mainly derived from coal and biomass combustion, and motor vehicle exhaust [23]. The seasonal average OC/EC ratios ranked as winter (2.5 ± 0.6) > fall

(1.8 ± 0.9) > summer (1.7 ± 0.7) > spring (1.5 ± 0.3). High OC/EC ratios in winter might be mainly attributed to more coal and/or biomass combustion for the heating in winter, which could emit more organic pollutants than vehicles [21]. In addition, stable atmosphere and low temperature in winter could facilitate the accumulation of air pollutants and accelerate the condensation or adsorption of volatile secondary organic compounds into aerosol [16,24]. The relatively high OC/EC in fall was due to some biomass burning after harvest which could release more organics than fossil fuel combustions [20]. In summer, high temperature and enhanced solar radiation were more favorable for SOC formation than spring. The results of OC/EC in different seasons were in agreement with the correlations between OC and EC. Comparing with other studies, the average OC/EC ratios in summer, fall and spring were lower than those in corresponding seasons in other Chinese cities (Table 1), while OC/EC in winter was comparable with most other cities in Table 1 (except for Xi'an, Beijing and average of 14 cities).

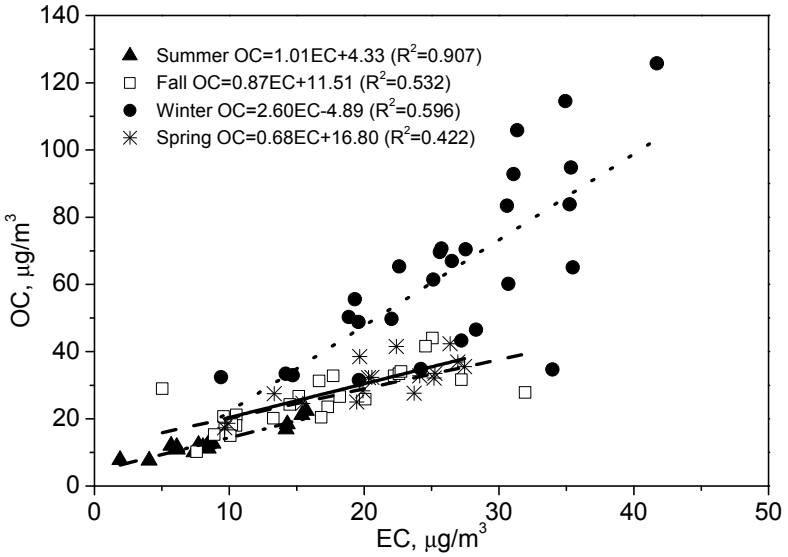

Figure 6. Seasonal correlations between OC and ECin $PM_{2.5}$ in Taiyuan.

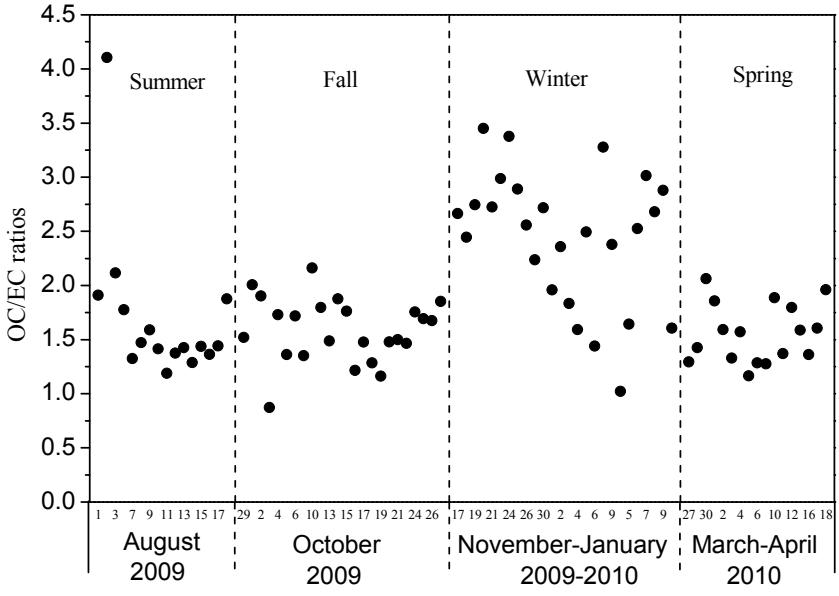

Figure 7. Seasonal variation of OC to EC ratios in $PM_{2.5}$ in Taiyuan.

3.4. Estimation of SOC and SOA Levels

According to Castro *et al.* [23], the minimum OC/EC ratio ($(OC/EC)_{min}$) method was used to estimate the second organic carbon (SOC) as the Equation (1) (TOC is the total OC).

$$SOC = TOC - EC \times (OC/EC)_{min} \quad (1)$$

As shown in Table 2, the annual average concentration of estimated SOC in $PM_{2.5}$ was 17.2 ± 18.9 μg/m^3 and accounted for 39.0% of OC, which was higher than that in Shanghai (27.0%–33.2% [4]). This result indicated that SOC was an important component of OC mass in Taiyuan. For inter-seasonal comparison, the highest SOC and its contribution to OC both occurred in winter *versus* the lowest in summer, and they differed by a factor of ~14 and ~2, respectively (Table 2). This result agreed with the studies on PRDR and Beijing conducted by Duan *et al.* [16] and Dan *et al.* [2]. However, it would be interesting to notice that the higher SOC in winter than summer as estimated in this study was contrary to the phenomena in another 14 cities over China (higher SOC in summer than in winter) in a study conducted by Cao *et al.* [11]. The highest concentration of SOC and SOC/OC ratio in being winter may be attributed to the two following reasons: firstly, the emission of (semi-)volatile organic compounds increased in winter for heating in Taiyuan, on the other hand low temperature enhanced the condensation of volatile secondary organic compounds in aerosol; secondly, the stable atmospheric condition in winter prolonged residence time, which could also enhance the condensation process.

The concentration of SOA was calculated by multiplying SOC by 1.6, which was listed in Table 2. The annual concentration of SOA was 27.5 ± 30.3 μg/m^3 and accounted for 12.2% of $PM_{2.5}$, which was higher than those in PRDR [16] and Shanghai [4]. The highest concentration of SOA and value of $SOA/PM_{2.5}$ in winter *versus* the lowest in summer were consistent with the result in PRDR [11] and different from those in Shanghai with highest values in fall [4]. The annual average percentage of 12.2% (higher than that in summer, fall and spring) indicated that SOA contributed a minor fraction of $PM_{2.5}$ mass in Taiyuan, although sometimes it could account for up to 23.7% in winter (Table 2). Furthermore, considering the important role of OC and EC in regional dust-haze, visibility reduction, atmospheric chemistry and human health, further studies on composition of carbonaceous particles in Taiyuan are still needed.

Table 2. Levels of second organic carbon (SOC) and SOA in Taiyuan estimated from minimum OC/EC ratios.

Season	$(OC/EC)_{min}$ [a]	SOC (μg/m^3)	POC (μg/m^3)	SOC/OC (%)	SOA [b] (μg/m^3)	$SOA/PM_{2.5}$ (%)
Annual	1.1 ± 0.1	17.2 ± 18.9	20.2 ± 9.5	39.0 ± 20.3	27.5 ± 30.3	12.2 ± 10.9
Summer	1.2	2.6 ± 1.5	10.5 ± 4.9	22.9 ± 17.6	4.2 ± 2.5	4.0 ± 4.3
Fall	0.9	11.0 ± 5.7	14.7 ± 6.2	42.8 ± 15.5	17.7 ± 9.1	10.5 ± 5.5
Winter	1.0	37.4 ± 21.6	25.4 ± 8.5	56.2 ± 14.6	59.8 ± 34.6	23.7 ± 11.3
Spring	1.1	7.8 ± 5.0	23.8 ± 8.7	25.9 ± 14.2	12.5 ± 8.0	5.5 ± 3.0

Values represent average ± one standard deviation. [a] The observed minimum ratio of OC/EC; [b] SOA is calculated by multiplying SOC by 1.6.

4. Conclusions

This study investigated the characteristics of $PM_{2.5}$, OC and EC in Taiyuan, the largest coal base of China. The concentration of $PM_{2.5}$ (220.2 μg/m^3) was higher than those in developed regions in China such as PRDR, Beijing and Shanghai, indicating the serious fine particle pollution in Taiyuan. The concentrations of OC (37.4 μg/m^3) and EC (19.6 μg/m^3) in Taiyuan were higher than most other cities such as Beijing, Guangzhou, Shanghai, Shenzhen, Zhuhai and Hong Kong (except for EC slightly lower than that in Beijing). Concentrations of $PM_{2.5}$, OC and EC in Taiyuan strongly varied with seasons in the following order: winter > spring > fall > summer. OC and EC (R^2 = 0.907) were well correlated in summer compared with fall, winter and spring (R^2 = 0.422–0.596), indicating that there existed biomass burning after harvest in fall, biomass burning and coal combustion for heating in winter and dust in spring. Higher OC/EC ratios in winter than those in other seasons might be attributed to more residential combustion of coal and biomass, low temperature and stable atmospheric condition. These results will be helpful for Shanxi province to set source emission control strategies for particulate matter.

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Author Contributions

The corresponding author of Qiusheng He designed the research theme and finished the manuscript. The $PM_{2.5}$ samples and all relevant data were collected by Wendi Guo, Guixiang Zhang and Yulong Yan. The co-corresponding author, Laiguo Chen was in charge of OC/EC analysis and relevant data interpretation.

Conflicts of Interest

The authors declare no conflict of interest.

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