Spatio-temporal Variation of PM$_{2.5}$ Pollution and its Relationship with Meteorology among Five Megacities in China

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ABSTRACT

Fine particles are a crucial air pollutant in terms of their impact on the ambient environment, citizens’ health and traffic visibility. In this study, temporal and spatial variations in PM$_{2.5}$ were analyzed in Beijing, Shanghai, Guangzhou, Chengdu and Shenyang in China from June 2013 till May 2017 using hourly data collected from the U.S. Embassy and Consulate monitoring system. The distributions of the annual, seasonal, monthly and diurnal concentration were illustrated by the attainment rate and the severity rate, as well as the length of time. After that, the coefficient of divergence (COD) was adopted to study the spatial heterogeneity among five typical megacities. Additionally, the relationship between PM$_{2.5}$ and meteorology was calculated by Pearson’s correlation and stepwise multiple linear regression. The results show that annual PM$_{2.5}$ concentrations were overall downward trends in all areas. Clear seasonal variations were identified, with the least pollution in summer and the most in winter. The hourly distribution was dramatically different, while the average concentration during the daytime was higher than at night except in Shanghai, and the weekends had higher pollution than the weekdays except in Chengdu. Also, the monthly attainment rate displayed an inverted-U distribution; oppositely, the severity rate revealed a U-shaped distribution. With the increasing pollution levels, the duration of the PM$_{2.5}$ pollution was observed to be continuously declining in Guangzhou, Shanghai and Beijing but fluctuating in the other two cities. Furthermore, COD values indicated that there was an obvious spatial heterogeneity between Beijing–Chengdu–Shenyang and Shanghai–Guangzhou. As for meteorology, the pressure had a significantly positive impact on the PM$_{2.5}$ concentration, while the temperature and rainfall had a negative influence. These results show the pollution levels of PM$_{2.5}$ in different cities at distinct times and confirm the important role of meteorological conditions in air quality. The findings also provide forecast models of PM$_{2.5}$ for the five cities.

Keywords: PM$_{2.5}$; Spatio-temporal variations; Meteorological parameters; Attainment and severity rate; Time length.

INTRODUCTION

The experience of many countries demonstrates that economic development will inevitably bring about a certain degree of environmental problems; China is no exception (Guo et al., 2017; Wang et al., 2017). Over the past decade, many large and medium-sized cities have suffered from serious PM$_{2.5}$ ambient pollution. PM$_{2.5}$ not only affects air quality (Zhang et al., 2015) and climate change (Fang et al., 2017) but also reduces visibility (Zhao et al., 2017) and threatens human health (Guo et al., 2016; Xie et al., 2016; Yang et al., 2017), especially the respiratory system (Bekki et al., 2016; Pollock et al., 2017). Since the haze events of China in 2013, the research on PM$_{2.5}$ has been increasing rapidly all around the world, mainly in spatio-temporal distribution (Jiang, 2015; Liu et al., 2016; Jin et al., 2017; Zhou et al., 2017) and composition (Lang et al., 2017; Wang et al., 2017; Xue et al., 2017), as well as relationships between PM$_{2.5}$ and meteorology (Bhaskar, 2010; Cheng, 2010; Huang et al., 2015; Chen et al., 2016), economy (Lin et al., 2013; Sun et al., 2016) and health risks (Bell, 2012; Lee, 2015). Meanwhile, spatio-temporal analysis is the hottest topic as a basic method that characterizes the spatial differences and time trend of PM$_{2.5}$ pollution.

The analysis of PM$_{2.5}$ temporal and spatial distribution is mainly divided into two categories. One is for signal sites and another for area study. The former is targeted at one or several cities (Lowsen and Conway, 2016; Gulia et al., 2017), such as megacities Beijing and Shanghai (Yan et al., 2016; Fontes et al., 2017). The latter is a hot area that is composed of multiple monitoring sites (Wang and Fang, 2016; Bran and Srivastava, 2017; Zikova et al., 2017), such as the Yangtze River Delta in China (Hu et al., 2014; Xu and Jiang, 2015), as well as the whole country as an object (Bhaskar, 2010; Bran and Srivastava, 2017; Guo et al., 2017).

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2017a; He et al., 2017; Song et al., 2017). The data sources generally fall under official statistics and field test data. Official statistics are obtained from the official websites or local environmental monitoring station, for instance, the Bureau of Statistics, Ministry of Environmental Protection (Guan et al., 2015; He et al., 2017). The latter refers to field measurements for which researchers set up their own equipment (Xu and Jiang, 2015; He et al., 2017). The span time of the study also varies: short-term for a typical period, such as a peak period of PM$_{2.5}$ (Zhang et al., 2017), medium term for several months or years (Guo et al., 2017b; Xu et al., 2017), and maybe long-term for more than 10 years (Wang et al., 2016; Xie et al., 2016). Moreover, the content focuses on the comparative analysis and correlation analysis of annual, seasonal, monthly, weekly and diurnal variability of PM$_{2.5}$ mass concentrations among different areas (Wang et al., 2014; Zhao et al., 2014; Fujii et al., 2016; Wang et al., 2017b). In general, the temporal and spatial study of PM$_{2.5}$ pollution is relatively comprehensive and can reflect the trend to some extent. However, there are still several problems in the process of studying. Firstly, how to select representative sites as research objects is particularly important, since only one or two cannot be representative, while too many may lack typicality. Secondly, especially in China, the current network platform is just for PM$_{2.5}$ real-time data. Open historical data is unavailable, not to mention hourly historical data; besides, the validity of historical data from non-official websites is questionable. Thirdly, the period after year 2016 is rarely addressed, as many monitoring sites have been deployed in recent years and focus on the data from 2010 till 2015 (Chen et al., 2016; Guo et al., 2017a; Sahu and Kota, 2017). Last but not least, pollution levels (Zhao et al., 2016), attainment days (Liang et al., 2015) and the duration of PM$_{2.5}$ (Liang et al., 2015) receive less attention, despite the fact that these indicators can reflect more aspects of a region regarding PM$_{2.5}$ pollution than just a single average.

Therefore, in order to better understand the pollution levels in the last few years since the government has implemented a series of regulations and limits to reduce PM$_{2.5}$ emission in China (Wang et al., 2017c), and provide basic data support for policy improvement and the introduction of new laws, five megacities with different climatic zones, terrain conditions and industrial development levels were selected, which can represent surrounding hotspot areas to a large extent (Fontes et al., 2017). At the same time, PM$_{2.5}$ mass concentrations with an hourly resolution from 2013 till 2017 were collected from automatic monitors of U.S. diplomatic missions in Beijing, Shanghai, Guangzhou, Chengdu and Shenyang. The monitor data is available to the public and was validated by Martini et al. in 2015 (Liang et al., 2015; San Martini et al., 2015). Then, a more comprehensive analysis, including temporal variations, the attainment and severity rate, the time length of the PM$_{2.5}$ pollution and spatial differences, as well as the correlation between PM$_{2.5}$ and meteorology among five cities in the last 4 years was conducted in this study.

**METHODOLOGY**

**Study Sites**

Five representative megacities, Beijing, Shanghai, Guangzhou, Chengdu and Shenyang, were selected in this study. For these five cities, the PM$_{2.5}$ pollution and meteorological conditions are substantially different. Besides, these regions were hot spots for pollution emissions studies in China because of their large population density, well-developed economy and severe ambient pollution (Zhang et al., 2015a; Wang et al., 2017c; Zhang et al., 2017). Beijing, the capital city of China and a center of politics, economy and culture, is located in the severely polluted North China Plain. Shanghai, as the busiest container port, is a coastal city with the largest population in China, and it is located in the Yangtze River Delta region in East China. Guangzhou, a vitally important national transport hub and a main trading port in the Pearl River Delta region, is the provincial capital of Guangdong province in southern China. Chengdu, as the provincial capital city of Sichuan province, is representative of inland cities located in southeastern China. Shenyang, the provincial capital of Liaoning province, is an industrial city in the northeast of China and located in the center of the Northeast Asian economic circle and Bohai economic circle. The five cities have different characteristics in geographical location, meteorological environment, industrial structure, socio-economic basis and air pollution; besides, all of them are regionally typical megacities in the surrounding urban agglomerations. Therefore, it is obviously necessary to conduct a comparative analysis between these five cities on PM$_{2.5}$ pollution study.

**Data Source**

PM$_{2.5}$ data from the U.S. Embassy and Consulate monitoring system of U.S. diplomatic missions in China was used in this study (Liang et al., 2015; San Martini et al., 2015; Lowsen and Conway, 2016; Fontes et al., 2017). Considering the data was monitored from April 23, 2013, in Shenyang, where the data collection date was later than other cities, so hourly averaged PM$_{2.5}$ data from June 1, 2013, till May 31, 2017, were selected in the five cities simultaneously. Monthly meteorological indicators, including temperature (T), relative humidity (RH), pressure (P), rainfall (R) and sunshine (S), were obtained only from June 2013 till December 2014 among different cities in China Meteorological Yearbook due to lack of data in the recent 3 years.

Beta attenuation monitors (BAM-1020, MetOne) were placed on the roofs of the U.S. Embassy in Beijing as well as the Consulates in four other cities to measure PM$_{2.5}$ (San Martini et al., 2015). The BAM method is an equivalent reference measurement at the U.S Environmental Protection Agency (EPA) for PM$_{2.5}$ analysis; details about the technical theory and operational approach can be found in EPA Standard Operating Procedures (2015). In this study, PM$_{2.5}$ hourly concentrations were filtered at first. Missing data and negative numbers were considered as invalid values and were therefore eliminated. Then the rest of the data was used to analyze the trends of PM$_{2.5}$ in the five
megacities during four-year periods, as shown in Table 1.

Chinese Ambient Air Quality Standards (CAAQS) (BG3095-12) provide a daily average concentration of 35 µg m⁻³ of PM₂.₅ for Grade I and 75 µg m⁻³ for Grade II and a yearly average of 15 µg m⁻³ for Grade I and 35 µg m⁻³ for Grade II. The World Health Organization (WHO) prescribes a standard value of 10 µg m⁻³. In this study, referring to the above criteria, the PM₂.₅ pollution was divided into five levels: excellent, good, mild, moderate and heavy. The corresponding daily average concentrations were 0–35, 36–75, 76–150, 151–300 and above 300 µg m⁻³. The attainment rate was defined as the proportion of excellent and good levels (a daily average concentration less than or equal to 75 µg m⁻³), and the severity rate was defined as the proportion of moderate and heavy levels (a daily average concentration greater than 150 µg m⁻³).

RESULTS AND DISCUSSION

Annual Variations

Fig. 1 demonstrated the annual trends of PM₂.₅ concentrations in five cities from 2014 till 2016; the years 2013 and 2017 were not included, since only 6 months of data were available. Beijing and Guangzhou had similar variations in that PM₂.₅ concentrations dramatically decreased year by year—the same results as other studies (Guo et al., 2017a; Wang et al., 2017c). PM₂.₅ concentrations in Chengdu had a declining trend during these years, but the rate of change was extremely low in 2016. Shanghai and Shenyang both slightly increased their concentrations from 2014 till 2015 and then obviously reduced them. All the cities presented an overall decreasing variation in 2016 compared with 2014; nevertheless, the annual average PM₂.₅ concentrations did not reach CAAQS Grade II during these years except in Guangzhou, whose concentration of 33.14 µg m⁻³ was a little lower than 35 µg m⁻³ in 2016. In general, PM₂.₅ concentrations in Beijing, Chengdu and Shenyang were around twice of those in Shanghai and Guangzhou. This phenomenon can be explained by the impact of the geographical location and climatic conditions. For Beijing, with mountains on the west and north sides and a large number of heavy industries to the east and south, it is easy for the continual southern wind to permeate PM₂.₅ or static weather to provide favorable conditions for the generation of secondary chemicals, which are difficult to spread. Shenyang, with mountains in the southeast, less precipitation and a low perennial temperature, is a heavy industrial city where the pollutants are easily generated. Chengdu, perennially wet

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Table 1. Overviews of study cities.

Fig. 1. Annual trends of PM₂.₅ concentrations in five cities.
with low winds and easy to form atmospheric suspended matter, is located in the Sichuan Basin, and its diffusion conditions are poor due to the mountains on the west and north sides. Regarding Shanghai and Guangzhou, their terrain is more open and closer to the sea; pollutants are easily blew away. Meanwhile, Guangzhou is near the Tropic of Cancer and has perennially high temperatures and an atmospheric boundary layer height that is greater than that of other cities, making it easy to dilute pollutants.

The proportions of the pollution levels among the five cities during the whole of the studied periods were different. Good levels accounted for the largest part in four of the cities, while Guangzhou had the highest proportion of excellent levels and no heavy pollution from 2013 till 2017, as described in Fig. 2(a). Attainment rates in Shanghai and Guangzhou were more than 84% but just nearly 60% in the other three cities. The severity rate in Beijing was the highest (14.17%), 29 times that of Guangzhou (0.49%) and 9 times of Shanghai. Furthermore, pollution of PM$_{2.5}$ improved gradually during these years. Excellent levels accounted for the largest part in Beijing, Shanghai and Guangzhou, while good levels occupied more than 50% in the other two cities. All the cities had the highest attainment rate in 2016 compared with two years before. The severity rate was reduced by 7.15%, 4.57% and 7.90% in Beijing, Chengdu and Shenyang, respectively, between 2014 and 2016.

**Seasonal Variations**

Ambient PM$_{2.5}$ concentrations displayed obvious seasonal patterns. The five cities had the same trends in that all curves were S-shaped variations from spring till winter, as presented in Fig. 3. The severest concentration was in winter, while the lowest pollution was in summer (Xu and Jiang, 2015; Song et al., 2017; Zhou et al., 2017); the ratio of winter to summer for PM$_{2.5}$ in Beijing, Shanghai, Guangzhou, Chengdu and Shenyang was 1.69, 2.11, 1.91, 2.13 and 2.28, respectively. It was illustrated that the changes among the four seasons were greater in Shenyang, Chengdu and Shanghai. PM$_{2.5}$ in autumn was higher than spring, besides Shanghai. In both spring and summer, the five cities, ranked from the severest to the slightest degree of pollution, were Beijing, Chengdu, Shenyang, Shanghai and Guangzhou. Moreover, the PM$_{2.5}$ in Beijing was nearly twice that of Guangzhou, and Chengdu had on average 1.5 times that of Shanghai in those two seasons. A different situation was observed in autumn, and the heaviest pollution was also in Beijing. Shenyang was the second most polluted city, as the values were 4.78 µg m$^{-3}$ more than those in Chengdu, and Shanghai, as the mildest city, had 2.37 µg m$^{-3}$ less than Guangzhou. The highest PM$_{2.5}$ was in Chengdu in

![Fig. 2](image-url)
Fig. 3. Seasonal variations in PM$_{2.5}$ concentrations among five cities.

winter, when the ranking of pollution was the same as in spring for the other four cities.

The proportions of the five pollution levels during the four seasons are implied in Fig. 4. In summer, good levels formed the highest proportion in all cities. Besides, Shanghai accounted for 63% in that level, 1.75 times that of Beijing. It is worth noting that there was no heavy level in the cities except Beijing; neither Shanghai nor Guangzhou had moderate pollution. For summer, the largest part of the pollution in Beijing, Chengdu and Shenyang was at the good level, while the largest part in Shanghai and Guangzhou was at the excellent level. There was no heavy pollution of PM$_{2.5}$ in the cities and no moderate pollution in Chengdu, Shenyang and Shanghai. All of the above indicates that the PM$_{2.5}$ pollution was gradually reduced from spring till summer. Good levels occupied the majority of autumn in the five cities, and the average pollution condition was greater than in the spring. There was an interesting phenomenon in that Beijing had the highest proportion of excellent level pollution among the five cities in winter as well as the highest season ratio in one year. That seemed to be the opposite of former results showing that the most serious pollution was in winter, as described in the last paragraph. Nevertheless, the different levels of PM$_{2.5}$ pollution for Beijing in winter were relatively balanced; the percentages of excellent, good, mild and moderate pollution were 28%, 22%, 23% and 21%, respectively, and the heavy pollution was higher (6%) than in other seasons (average of 2.5%). So, Beijing had a relatively extreme situation in terms of both high ratios of excellent quality and severity rates. Mild pollution accounted for 32% and 21% of the total in Shanghai and Guangzhou during winter, while the values did not exceed 11% for the two cities in other seasons. In addition, the most frequent pollution level in Chengdu and Shenyang was mild in the winter, while good was the most frequent at other times. PM$_{2.5}$ moderate pollution was also the highest from December till February among the five cities. All of the above indicates that the PM$_{2.5}$ pollution was the severest in winter but the mildest in summer.

Monthly Variations

Monthly average PM$_{2.5}$ differences were calculated as follows: the values in the latter year (target year) minus those of the base year, 2014. Three categories from bottom to top for 2015–2014, 2016–2014 and 2017–2014 in each city are shown in Fig. 5. The columnar shape on the left side of the ordinate implies that the difference was negative—that is, the PM$_{2.5}$ concentrations were lower compared to 2014—and a longer length means a greater change. Inversely, the values on the right represent the increasing concentrations. Changes between different target years can be observed by comparing the categories. The number of columnar on the left side is clearly more than the right side in each city, which indicates that the months of the reduction was significantly more than the increase between the target year and the base year, and the decrease in concentrations was also greater than the increase. For Beijing and Chengdu, PM$_{2.5}$ values in the latter years mainly rose in November and December compared to 2014. The amount of change in 2016 was lower than in 2015, exhibiting a decreasing trend in PM$_{2.5}$ pollution, while the start of 2017 showed a relatively significant increase. A common situation, an increase in February and August every year, was found in Shanghai and Guangzhou; however, the concentrations in Shanghai for the last 13 months were lower when compared with historical data of the same months. The values in Shenyang grew by an average of 24.33 µg m$^{-3}$ in the first and the last two months in 2015 and then dropped steeply in 2016; they slightly rose in 2017 but at a lower rate than in 2015.

The attainment rate and severity rate for 12 months in
Fig. 4. The proportion of pollution level among five cities in four seasons.

Fig. 5. Monthly PM$_{2.5}$ pollution differences in each city.
different cities are presented in Fig. 6. Guangzhou had the highest attainment rate in almost every month except October, while Beijing had the lowest rate from March till October and Chengdu had the lowest from December till February. The order of the cities in terms of the average attainment rate from high to low was Guangzhou (90%), Shanghai (85%), Shenyang (68%), Chengdu (62%) and Beijing (59%), and the standard deviations in these cities were 10%, 16%, 23%, 25% and 10%, respectively. For the severity rate, the highest values emerged in Beijing except during January, when Chengdu was 16% more than Beijing, while in August, only Shenyang was 1%, and the other cities were 0%. The order of the average severity rate from high to low was Beijing (14%), Shenyang (8%), Chengdu (7%), Shanghai (2%) and Guangzhou (0%). The standard deviations in those cities were 12%, 9%, 13%, 3% and 1%, respectively. Therefore, the analysis of the monthly variation suggested that the heaviest PM$_{2.5}$ pollution was in Beijing and the slightest in Guangzhou, which had the highest attainment rate and the lowest severity rate as well as the lowest standard deviation. Shanghai was worse than Guangzhou, with the second highest attainment rate and the second lowest severity rate. The monthly attainment rates of PM$_{2.5}$ in Chengdu (62%) and Shenyang (68%) were higher than Beijing (59%); even so, the standard deviations in these two cities (25% and 23%) were higher than that of Beijing (10%), revealing that overall pollution was severe in Beijing during the majority time of one month, while relatively milder conditions with some extreme monthly indicators could be emerging in Chengdu and Shenyang. In the case of the severity rate in Beijing and Chengdu, a situation was observed that was analogous to the attainment rate. Furthermore, the figure of the attainment rate was an inverted U-shaped distribution, whereas, on the contrary, the severity rate implied a U-shaped distribution; both illustrated that the PM$_{2.5}$ pollution from April till September was dramatically lower than for other months in all the cities.

### Diurnal Variations

The variations in 24 hours during whole periods were observed by radar chart. The graph of Beijing, which is similar to a circle in the upper center, was different from other cities, as displayed in Fig. 7(a). A U-shaped trend from 0 a.m. to 23 p.m. showed heavier concentrations at night and lower values during the daytime. Similar curves like the number “8” appeared in Shanghai and Guangzhou, indicating low values in the morning and afternoon and high values in the evening. The difference between these two cities was that Shanghai varied bi-modally at 9 a.m. and 19 p.m. but just one peak was observed at 20 p.m. in Guangzhou. Moreover, a heart shape was discovered in the bottom right for both Chengdu and Shenyang, indicating heavy pollution in the morning and light pollution in the afternoon. The trends of diurnal variability were consistent with the previous study except for Shanghai (San Martini et al., 2015). In addition, the lowest and the highest hourly PM$_{2.5}$ concentrations during one day were different in the five cities at different times, varying from 72.65 (15 p.m.)
to 96.34 (1 a.m.), 47.24 (19 p.m.) to 52.59 (19 p.m.), 39.50 (16 p.m.) to 46.76 (20 p.m.), 65.96 (17 p.m.) to 85.50 (9 a.m.) and 53.95 µg m\(^{-3}\) (15 p.m.) to 83.89 µg m\(^{-3}\) (8 a.m.) for Beijing, Shanghai, Guangzhou, Chengdu and Shenyang, respectively. The large hourly rate of change in Shenyang and Beijing but narrow gap in Guangzhou and Shanghai can be derived. It should be mentioned that the average hourly PM\(_{2.5}\) in Beijing (84.16 µg m\(^{-3}\)) was dramatically higher than that in Shenyang (70.56 µg m\(^{-3}\)), yet the range of variation in the former city (23.69 µg m\(^{-3}\)) was smaller than in the latter (29.94 µg m\(^{-3}\)). It was proved that relatively heavier pollution was in Beijing during the whole day, while lighter pollution but several extreme hourly values occurred in the morning in Shenyang. A similar situation was identified for Guangzhou, which had milder PM\(_{2.5}\) pollution than Shanghai during most of the hours but also some extreme values.

Trends of the hourly average PM\(_{2.5}\) for the whole time, the weekends and the weekdays were consistent, as revealed in Fig. 7. The 24-hour values of the whole period were between the values of the weekends and the weekdays. It was notable that the pollution on workdays was heavier than the weekends just in Chengdu. There were narrow differences in pollutant concentrations among three analysis periods at corresponding hours in Guangzhou and Chengdu; nonetheless, the large gap between the weekends and the weekdays was discovered in other cities. Furthermore, the differences in hourly concentrations between weekends and working days were not the same in the five cities. The maximum difference appeared at the moment of the highest concentration except in Chengdu, where the minimum difference occurred at the time of the severest pollution.

PM\(_{2.5}\) pollution was not the same during the day and night. The daytime was defined from 6 a.m. to 20 p.m. and the night from 21 p.m. to 5 a.m. in this study. The average hourly PM\(_{2.5}\) during the day and night during the three analysis periods is shown in Fig. 8. It was suggested that pollution in Beijing, Chengdu and Shenyang was about twice that of Shanghai and Guangzhou. More important, pollution at night was heavier than that during the day in all cities aside from Shanghai, the only city that had the opposite phenomenon. In addition, the differences between PM\(_{2.5}\) for day and night were significant in Beijing and Shenyang. This may result from the longer residence time of PM\(_{2.5}\) due to more heavy factories and regional meteorological conditions being unfavorable for PM\(_{2.5}\) diffusion at night.

**Length of Time**

The duration of the PM\(_{2.5}\) concentration at different pollution levels represents the severity of the particle pollution. At excellent and good levels, the longer duration indicates greater ambient conditions. On the contrary, at mild, moderate and heavy levels, the longer length of time indicates worse air quality and a more negative impact on
human health. Fig. 9(a) illustrates the length of time of PM$_{2.5}$ varying from 1 to 4.15 days for five levels during the whole period of study. With the increasing pollution levels, the duration of PM$_{2.5}$ pollution decreased rapidly in Guangzhou and Shanghai and decreased gradually in Beijing. It revealed that severe PM$_{2.5}$ pollution would not last for a long time in those cities. Shenyang had a slight increase in duration from the excellent to the good level and then a slow reduction. Notably, the duration time in Chengdu was fluctuating; furthermore, the mild and moderate levels both had the longest durations in this area compared with other cities. This trend indicated that Chengdu had severer pollution, which did more harm to the body, than other areas to some extent when PM$_{2.5}$ concentrations exceeded 150 µg m$^{-3}$.

The length of time of PM$_{2.5}$ was also different between seasons. In spring, the variation was from 1.5 to 2 days in Beijing, which was obviously less than in other cities, as seen in Fig. 9(b). It indicated a quick change in PM$_{2.5}$ concentration and unstable air pollution in Beijing. Moderate and heavy pollution did not occur in Shanghai, which was consistent with the analysis in the section of seasonal variation. For Guangzhou, the largest difference among five levels (1.87 days) was identified. The long-term attainment level and short-term pollution indicated fine air quality. Pollution in summer dramatically differed from other seasons, with the largest ratio among different pollution levels. This trend was the opposite of the situation in winter. It was calculated that the highest average length of time among the five levels was in summer in all the cities, while the lowest was in winter. All of the above confirmed that the PM$_{2.5}$ was less in summer and pollution was severe in winter.

**Spatial Variations**

The spatial heterogeneity of PM$_{2.5}$ concentrations can be measured by the coefficient of divergence (COD) (Guo et al., 2017b; Song et al., 2017). A value of COD is between 0 and 1, and the higher the value is, the greater the heterogeneity is. Moreover, a COD larger than 0.2 indicates that the spatial heterogeneity of PM$_{2.5}$ concentration has begun to vary. The COD is defined as

$$COD_{ij} = \left(1 - \frac{1}{n} \sum_{t=1}^{n} \left( \frac{x_{it} - x_{jt}}{x_{it} + x_{jt}} \right)^2 \right)^{1/2}$$  \hspace{1cm} (1)

where $COD_{ij}$ is the coefficient of divergence between site $i$ and site $j$, $x_{it}$ and $x_{jt}$ are PM$_{2.5}$ concentrations during time $t$ at site $i$ and site $j$ and $n$ is the amount of time.

Correlation analysis can also be used to investigate the spatial relationship between different regions (Hu et al., 2014; Fang et al., 2017). A positive correlation coefficient indicates the same trend; the closer to 1 it is, the better the degree of correlation.

The COD values for the mean monthly PM$_{2.5}$ among 5 cities are calculated in the upper right of Table 2. The values larger than 0.2 are shown in bold font. They represented significantly different spatial distribution between two cities. The five cities were divided into two categories: one included Beijing, Chengdu and Shenyang, and the other included Shanghai and Guangzhou. High COD values were observed when a city in the former category was compared with a city in the latter category, while low values of less than 0.2 were seen when two cities were in the same category. This phenomenon implies that the heterogeneous spatial variations between Category 1 (Beijing, Chengdu, Shenyang) and Category 2 (Shanghai, Guangzhou) are consistent with the previous analysis, which indicated that the PM$_{2.5}$ concentrations in the first category were higher than those in the second.
Fig. 9. Duration of PM$_{2.5}$ pollution in the whole period from June 2013 till May 2017 (a) and in the four seasons (b–e).

Table 2. The COD values for monthly averaged PM$_{2.5}$ concentrations among five cities (upper right) and Pearson correlation coefficients for daily PM$_{2.5}$ concentrations (bottom left).

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The Pearson correlation coefficients for daily PM$_{2.5}$ concentrations are presented in the bottom left of Table 2. All the coefficients demonstrated that there were positive correlations among five cities. Values above 0.3 are shown in bold font and represent a relatively high correlation between two cities. For instance, the highest coefficient, 0.45, indicated that Beijing and Shenyang had a high correlation, as both their levels of PM$_{2.5}$ were higher than those for the other three cities, while the lowest coefficient, 0.06, indicated that Beijing and Shanghai had an obvious difference in PM$_{2.5}$ because of the most serious PM$_{2.5}$ pollution occurring in Beijing. These results were similar to the outcomes of the COD analysis, and Beijing, Chengdu and Shenyang were apparently different from Shanghai and Guangzhou in environmental PM$_{2.5}$.

**Relationship between PM$_{2.5}$ and Meteorology**

Monthly averaged meteorological factors, including T, RH, P, R and S, were directly obtained from China Meteorological Yearbook. Due to lacking data for the last 3 years, only the data for 18 months, from June 2013 till December 2014, for the five cities was analyzed. Table 3 reveals the average values of the monthly data for PM$_{2.5}$ and meteorological factors. The hourly PM$_{2.5}$ mass concentrations were firstly calculated into monthly mean values to correspond with the monthly meteorological values and then the correlation coefficients were calculated.

The relationship between PM$_{2.5}$ and meteorological parameters was calculated by Pearson correlation analysis, as shown in Table 4. It is noted that only P presented a positive correlation with PM$_{2.5}$ in all cities, while other factors...
Table 3. Averaged PM$_{2.5}$ and meteorology of 18 months.

<table>
<thead>
<tr>
<th>City</th>
<th>PM$_{2.5}$ (µg m$^{-3}$)</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>P (KPa)</th>
<th>R (mm)</th>
<th>S (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>94.60</td>
<td>15.16</td>
<td>54.84</td>
<td>1011.85</td>
<td>52.34</td>
<td>194.45</td>
</tr>
<tr>
<td>Shanghai</td>
<td>50.62</td>
<td>18.70</td>
<td>71.58</td>
<td>1015.26</td>
<td>111.37</td>
<td>145.70</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>49.29</td>
<td>22.27</td>
<td>78.68</td>
<td>1004.24</td>
<td>187.37</td>
<td>148.78</td>
</tr>
<tr>
<td>Chengdu</td>
<td>81.27</td>
<td>17.12</td>
<td>81.47</td>
<td>950.71</td>
<td>113.87</td>
<td>78.28</td>
</tr>
<tr>
<td>Shenyang</td>
<td>72.27</td>
<td>10.67</td>
<td>63.79</td>
<td>1009.42</td>
<td>54.17</td>
<td>212.25</td>
</tr>
</tbody>
</table>

Table 4. Pearson correlation coefficients between PM$_{2.5}$ and meteorology in five cities.

<table>
<thead>
<tr>
<th>City</th>
<th>T</th>
<th>RH</th>
<th>P</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>−0.57*</td>
<td>−0.86</td>
<td>0.60**</td>
<td>−0.50*</td>
<td>−0.09</td>
</tr>
<tr>
<td>Shanghai</td>
<td>−0.78**</td>
<td>−0.29</td>
<td>0.69**</td>
<td>−0.55*</td>
<td>−0.74</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>−0.70**</td>
<td>−0.68**</td>
<td>0.71**</td>
<td>−0.55*</td>
<td>−0.35</td>
</tr>
<tr>
<td>Chengdu</td>
<td>−0.83**</td>
<td>−0.29</td>
<td>0.78**</td>
<td>−0.58**</td>
<td>−0.16</td>
</tr>
<tr>
<td>Shenyang</td>
<td>−0.84**</td>
<td>−0.45</td>
<td>0.85**</td>
<td>−0.64**</td>
<td>−0.38</td>
</tr>
</tbody>
</table>

** and *: Correlation is significant at the 0.05 and 0.01 levels (2-tailed).

had negative impacts on PM$_{2.5}$ concentrations. Besides, P, T and R were significantly correlated with PM$_{2.5}$. Specifically, high T favors the dispersion of secondary pollutants (Fang et al., 2017), and the phenomenon could also be seen in seasonal variability—the higher the temperature, the lower the PM$_{2.5}$. Moreover, P was usually inversely proportional to T so that positively related to air pollution (Zhao et al., 2013). Furthermore, the plentiful rainfall benefited the removal of ambient pollution, similar to the previous studies (Cheng, 2010; Connan et al., 2013; Zhang et al., 2015b; Ma and Jia, 2016) illustrating that PM$_{2.5}$ concentrations would decrease with the accumulation of R owing to wet scavenging. However, RH and S were negative but at a non-significant level. In general, S was a signal of great weather with relatively high wind speeds or little cloud cover (Sanchez-Romero et al., 2014), which was favorable for the decrease of PM$_{2.5}$. On the contrary, the reduction of RH was often accompanied by a short sunny period, cloudy and windless (Kang et al., 2013), which resulted in the increase of pollution. The non-significance might be caused by the different time as well as distinct areas with varied meteorology. For Beijing, P had the highest positive relationship with PM$_{2.5}$, while T and R both had significantly negative correlations. In the case of Shanghai, PM$_{2.5}$ and meteorological parameter correlation coefficient values varied from −0.29 to −0.78. T had the most obvious influence on PM$_{2.5}$ in this area; P and R were the second and the third factors, respectively. Guangzhou was different from the other cities because RH had the second highest negative impact on PM$_{2.5}$. Furthermore, Chengdu resembled Shanghai in that T was the most important influencing factor. The correlations in Shenyang were similar to those in Beijing. P, T and R were also the top three parameters for significantly impacting local PM$_{2.5}$. In general, T and R were anti-correlated with PM$_{2.5}$ pollution in all studied sites; on the contrary, P had a significantly positive impact on PM$_{2.5}$. Furthermore, there were no significant correlations among RH, S and PM$_{2.5}$.

For further analysis, the relationship between PM$_{2.5}$ and meteorology was quantified in five different cities, and the linear regression method was adopted. When five meteorological parameters and local PM$_{2.5}$ were input, the regression results implied no significance in all cities. This was because there were relatively high correlations among five meteorological factors. Therefore, stepwise multiple linear regression should be used to avoid multiple collinearity, and the results are presented in Eq. (2).

Beijing: PM$_{2.5}$ = 0.19P − 0.45S − 0.20R, R$^2$ = 0.98 (2)
Shanghai: PM$_{2.5}$ = 0.09P − 2.09T, R$^2$ = 0.93
Guangzhou: PM$_{2.5}$ = 0.15P − 1.16T − 0.95RH, R$^2$ = 0.95
Chengdu: PM$_{2.5}$ = 0.13P − 3.80T + 0.25S, R$^2$ = 0.98
Shenyang: PM$_{2.5}$ = 0.09P − 1.78T, R$^2$ = 0.96

Stepwise regression indicated that the correlations between PM$_{2.5}$ and meteorological parameters were not the same in different cities, though P and T had significant impacts on regional PM$_{2.5}$ in most of the cities. The higher the air pressure and the lower the temperature, the severer the PM$_{2.5}$ pollution.

CONCLUSIONS

In this study, five typical cities in China, namely, Beijing, Shanghai, Guangzhou, Chengdu and Shenyang, were analyzed to explore the temporal and spatial distribution of PM$_{2.5}$. Then, the relationship between PM$_{2.5}$ and meteorological parameters, such as the temperature, relative humidity, air pressure, rainfall and sunshine, were investigated by Pearson’s correlation and the stepwise multiple regression method. The PM$_{2.5}$ hourly data was selected from the period between June 2013 and May 2017 from the U.S. Embassy and Consulate monitoring system; at the same time, monthly meteorological data from the China Meteorological Yearbook for June 2013–December 2014 was used. The annual, seasonal, monthly and diurnal variations among five cities exhibited different temporal distributions. The average annual PM$_{2.5}$ exceeded CAAQS Grade II expect for Guangzhou in 2016, indicating that the megacities are still experiencing severe pollution, though the overall conditions have improved in recent years.
Moreover, summer had the lowest concentrations, because of high temperatures, whereas the heaviest pollution was in winter, owing to cold weather, high pressure and coal combustion. Furthermore, the five cities could be divided into two categories by analyzing the attainment rate, severity rate, length of time and spatial heterogeneity. Category One comprised Beijing, Chengdu and Shenyang, which had severer PM$_{2.5}$ all year round than Category Two, which comprised Shanghai and Guangzhou.

This study reveals a basic scenario of PM$_{2.5}$ pollution in five typical cities in China and builds linear-regression forecasting models between PM$_{2.5}$ concentrations and meteorological parameters. However, monthly mean meteorological indicators rather than hourly (or daily) indicators were used due to the lack of data, so the correlation analysis was limited in explaining intraday variability, although a general trend of impact could be obtained. Further studies should explore in depth the correlation between meteorology and PM$_{2.5}$ if hourly meteorological data can be obtained. Besides, PM$_{2.5}$ concentrations may not just be influenced by the aforementioned meteorological factors; other parameters, such as the wind speed, wind direction and mixed layer height, should be further considered to conduct more comprehensive research (Chen et al., 2016; Zhao et al., 2017). Additionally, the severity of fine particle pollution in a city cannot be expressed by a certain value, and every city also has its own geographical conditions and socioeconomic level, which may impact the formation and diffusion of PM$_{2.5}$. Therefore, an accurate and objective method for evaluating PM$_{2.5}$ pollution among different areas is still under development.

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