A Study of Characteristics and Origins of Haze Pollution in Zhengzhou, China, Based on Observations and Hybrid Receptor Models

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ABSTRACT

To obtain a comprehensive picture of characteristics and sources of haze pollution in Zhengzhou, we analyzed annual air pollutant (fine particulate matter (PM2.5), inhalable particulate matter (PM10), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2) and ozone (O3)) observations at nine monitoring stations from March 1, 2013 to February 28, 2014. A case study on haze pollution was carried out using observations, metrological data, aerosol optical depth (AOD) values and Hybrid receptor models. Results of annual variations of air pollutants indicated that PM2.5 pollution in Zhengzhou was the most severe. Monthly variations revealed that all air pollutants except O3 showed peak values in December because of the increased local emissions during heating, while the lowest value found in August was probably because of the favorable dispersion conditions. The monthly variation patterns of O3 concentrations show the peak values in August due to higher temperature and stronger solar radiation. The diurnal variations showed that PM2.5 concentration variations were consistent with the traffic flow. The high values of PM2.5/PM10 and PM2.5/CO occurred in the afternoon probably due to the strong photochemical reactions. Results of the case study showed that relative humidity and wind speed were the main meteorological factors influencing PM2.5 concentrations. Back trajectories show that regional transport from the northeast and southeast of Zhengzhou (such as Puyang, Kaifeng, Zhoukou, and Xuchang in Henan province) also made a big contribution to the PM2.5 pollution in Zhengzhou. Our results demonstrated that the spatial-temporal distributions of PM2.5 in Zhengzhou were determined by complex factors such as primary emissions, secondary production, meteorological conditions and local/regional-transport.

Keywords: Haze; Primary emissions; Meteorological factors; Potential sources.

INTRODUCTION

China has made phenomenal progress in economic growth in the past few decades because of unprecedented urbanization and industrialization. This rapid growth has led to dramatic and widespread decline in the quality of the environment, especially in air quality (Hao and Wang, 2005; Chan and Yao, 2008; Chang et al., 2009; Yu et al., 2016). Studies have proved that fine particulate matter (PM2.5) is one of the major air pollutants which cause the severe haze (McKeen et al., 2007; Tan et al., 2009; Bao et al., 2010; Eder et al., 2010; Zhang et al., 2010; Yang et al., 2012; Yu et al., 2014a). There have been plenty of evidences that PM2.5 is associated with morbidity and mortality (Dockery et al., 1993; Brunekreef and Forsberg, 2005; Tong et al., 2009; Pope and Dockery, 2012). The increased concentrations of PM2.5 can lead to climate changes due to their direct and indirect effects (Shao et al., 2006; Yu et al., 2006a; IPCC, 2007; Hyslop, 2009; Wang and Hao, 2012; Yu et al., 2014b, c). PM2.5 can also make a significant impact on atmospheric properties during their global transport processes (Yang et al., 2005; Wang et al., 2015a, b, c). China has frequently suffered from haze pollution, which was characterized by more episodes, longer duration and higher pollutant concentration levels, especially in the densely-populated and highly-industrialized eastern China (Tao et al., 2014; Liu et al., 2016).

Zhengzhou is the capital of Henan province with total population of 11 million and land area of 7446 km2. Zhengzhou has a typical temperate continental monsoon climate, characterized by prevailing northerly wind in
winter and prevailing southerly wind in summer. In 2013, the Gross Domestic Product in Zhengzhou was ¥ 620.2 billion (Henan Statistical Yearbook, 2014). As one of major hubs of transportation and communication in China, Zhengzhou is in the boom of industrial development with the worsening air pollution in future. Wang et al. (2015a) showed that the air in winter is heavily polluted in Zhengzhou, mainly due to the emissions from heating. Geng et al. (2013) studied chemical composition and source apportionment of PM$_{2.5}$ in Zhengzhou in 2010. They found that there were three main sources (soil dust, secondary aerosols and coal combustion) which contributed 26%, 24% and 23% of the PM$_{2.5}$ concentration respectively. The Department of Environmental Protection of Henan province published the results of PM$_{2.5}$ source apportionments in 2015, indicating that dust was the largest source of PM$_{2.5}$ in Zhengzhou urban area with contribution of 24.5%, while industry, coal and vehicle emissions contributed 26%, 24% and 23% of PM$_{2.5}$ concentrations, respectively.

Zhengzhou has suffered from air pollution for years, and the air pollution in Zhengzhou often ranked among top ten worst cities in China. However, the regional haze episodes in Zhengzhou have not yet been studied systematically. The objectives of this study are to identify the characteristics and sources of main air pollution and examine the underlying formation mechanisms which would help to guide the development of the emission control strategies to reduce regional hazes in Zhengzhou in future. In this study, we analyzed air pollutant (PM$_{2.5}$, PM$_{10}$, NO$_2$, CO, SO$_2$ and O$_3$) observations from March 1, 2013 to February 28, 2014. Meteorology and satellite observational data, and hybrid receptor models were also employed to analyze the sources and formation mechanisms of haze pollution in Zhengzhou.

DATA AND METHODOLOGY

Air Monitoring Stations

Fig. 1 indicates the distribution of nine monitoring stations in Zhengzhou: Yanchang (34.75°N, 113.68°E) and Heyida (34.75°N, 113.64°E) located in the transportation hub and business district, Zhengfangji (34.77°N, 113.64°E) and Shijiancezhan (34.75°N, 113.60°E) located in the industrial and residential area, Yinhangxuexiao (34.80°N, 113.67°E), Gongshuigongsi (34.80°N, 113.56°E), Jingkaiqiguanshi (34.72°N, 113.73°E) and Sishiqizhong (34.72°N, 113.73°E) located in the cultural and educational area, while Ganglishuiku (34.92°N, 113.61°E) is the background station. This study used hourly air pollutants (PM$_{2.5}$, PM$_{10}$, NO$_2$, CO, SO$_2$ and O$_3$) data at nine urban monitoring stations from March 1, 2013 to February 28, 2014 obtained from China National Environmental Monitoring Center (CNEMC) (http://106.37.208.233:20035/) and meteorological data (http://www.wunderground.com/cn/zhengzhou/zmw:000001.WZHCC).

Satellite Observations

Moderate Resolution Imaging Spectroradiometer (MODIS) is a main sensor aboard the satellites EOS/Terra and EOS/Aqua. The aerosol loading in the atmosphere can be described by the Aerosol Optical Depth (AOD) retrieved from satellite sensors. AOD has been widely considered to be a useful tool for mapping air pollution distribution over large spatial domains (Chu et al., 2003; Wang and Christopher, 2003; Guo et al., 2009; Zhang and Reid, 2010; Wu et al., 2012). To study spatial characteristics of haze, this work used the Deep Blue daily AOD data at 550 nm obtained from MOD08_D3 data (Level–3 data) on NASA’s Terra.

![Fig. 1. Distributions of air quality monitoring stations in Zhengzhou City.](image)
satellite with a 1° spatial resolution during December 11–29, 2013 (http://giovanni.sci.gsfc.nasa.gov/giovanni/). Xin et al. (2014) showed that there were high correlations between the observed AOD and MODIS AOD when the Angstrom exponent was less than 1.5 and that the slopes decreased from 0.97 to 0.83 with the Angstrom exponent increasing (the dominant aerosol size decreasing). Therefore, the MODIS AOD data are good for this study.

**Back Trajectory and Cluster Analysis**

Air mass back trajectories were calculated using the National Ocean and Atmospheric Administration (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (http://ready.arl.noaa.gov/HYSPLIT.php) and meteorological data supplied by the NOAA/Air Resources Lab (NOAA/ARL, http://ready.arl.noaa.gov/gdas1.php) and Global Data Assimilation System (GDAS). In this study, 48 hr back trajectories starting at the arrival level of 100 m from nine urban monitoring sites in Zhengzhou were calculated to explain when and where the pollutants were potentially transported (Brankov et al., 1998; Wang et al., 2009; Yu et al., 2014a). In this study, 48 hrs was chosen to calculate the back trajectories because it was sufficient to locate possible regional transport pathways (Yu et al., 2014a; Yan et al., 2015). According to meteorological fields, the backward trajectory model was run eight times per day at starting times of 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 LT (local time). The trajectory cluster analysis was performed with the clustering option of Euclidean distance (Wang et al., 2009; Yu et al., 2014a; Yan et al., 2015).

**Receptor Model Description**

Identifying the origins of the pollutants and distinguishing between long range and local contributions could give government crucial information for the implementation of effective control strategies. Concentration Weighted Trajectory (CWT) method was introduced to confirm the influence of air masses transported from heavily-polluted area at the receptor site (Ashbaugh et al., 1985; Hsu et al., 2003; Yu et al., 2014a; Li et al., 2015). The CWT method computes the concentration at the receptor site weighted by the residence time of the trajectory for each grid cell. The high CWT values reveal that air parcels arriving at the grid cell can contribute to high pollutant values at the receptor site.

**DISCUSSION AND RESULTS**

**Temporal Variations of Air Pollutants**

*Annual Variations of Air Pollutants*

The annual average concentrations of SO$_2$, O$_3$, and CO were 53.94 µg m$^{-3}$, 45.21 µg m$^{-3}$, and 2.43 mg m$^{-3}$, respectively, and did not exceed the corresponding Chinese National Air Quality Secondary Standard (CNAQSS) (60 µg m$^{-3}$ for SO$_2$, 200 µg m$^{-3}$ for O$_3$, 4.0 mg m$^{-3}$ for CO) (because there are no annual CNAQSS for O$_3$ and CO, we used 1 h and 24 h CNAQSS to evaluate O$_3$ and CO pollution). For the whole study period, the hourly concentrations of SO$_2$ ranged from 5 to 486 µg m$^{-3}$, with the highest concentration close to the corresponding hourly CNAQSS of 500 µg m$^{-3}$. The SO$_2$ concentrations in urban atmospheric environment are directly affected by various pollution sources, such as thermal power plants, sulphur production and other high-sulfur coal combustion. The economy in Zhengzhou is still highly dependent on industry, especially heavy industry, with more than 70% of the primary energy consumption from coal (ZMBS, 1999–2009). The annual average concentrations of PM$_{2.5}$, PM$_{10}$ and NO$_2$ were 97.17 µg m$^{-3}$, 157.22 µg m$^{-3}$, and 50.01 µg m$^{-3}$, respectively, and exceeded their corresponding CNAQSS (35 µg m$^{-3}$ for PM$_{2.5}$, 70 µg m$^{-3}$ for PM$_{10}$, and 40 µg m$^{-3}$ for NO$_2$) by 277.63%, 224.60%, and 125.03%, respectively. The primary sources of NO$_2$ emissions are motor vehicles, power plants and residential energy consumption. The heavy traffic flow led to the high NO$_2$ emissions in Zhengzhou because of its role as an important transportation hub in China. The PM$_{2.5}$ is major pollutant in 2013, with 65% of days exceeded AQI standard and is responsible for 77% of the polluted days in Zhengzhou (ZZEPB, 2013). These results suggested that PM$_{2.5}$ pollution in Zhengzhou was very severe and should remain a concern.

*Monthly Variations of Air Pollutants*

In this study, we grouped 12 months into four seasons: spring (March, April and May), summer (June, July and August), autumn (September, October and November) and winter (December, January and February). As shown in Fig. 2, all of these air pollutants except O$_3$ showed high values in winter months due to the heating period and low values in summer months because of the favorable diffusion and dilution conditions. The O$_3$ concentrations have opposite monthly variation pattern with peak value occurring in August due to the higher temperature and stronger solar radiation.

PM$_{2.5}$ and PM$_{10}$ concentrations showed similar variation patterns: winter > autumn > spring > summer. In winter, the increased emissions from heating and low planetary boundary layer (PBL) may enhance PM concentrations and induce slower pollutant diffusion (Liu et al., 2013). In spring and autumn, local particles are re-suspended in the atmosphere due to strong winds, which could also increase the PM concentrations (Deng and Li, 2015). In summer, the favorable diffusion and dilution conditions could decrease the concentrations of PM (Yoo et al., 2014). Fig. 2 showed two peaks of PM$_{2.5}$ and PM$_{10}$ concentrations in October and December, which were mainly caused by the biomass burning and increased coal consumption during the heating period, respectively (Zheng et al., 2014). As shown in the white paper of Zhengzhou "blue sky" project (2013–2015) (http://www.henan.gov.cn/jrhn/system/2013/04/22/010386360.shtml), Zhengzhou city increased the total GDP from 166.1 billion to 554.7 billion Yuans, expanded the built-up area from 262 to 373 km$^2$, increased the total coal consumption from 21.12 million tons to 35 million tons, and increased the number of vehicle from 0.985 million to 2.105 million for the period of 2005 to 2012. On the other hand, on the basis of the national remote sensing monitoring of straw burning points released by the Ministry of Environmental Protection from October 6 to October 12, 2014, the number of straw burning points in Henan was
245, the highest in the country. According to Zhengzhou Environmental Protection Bureau, the increased concentrations of PM$_{2.5}$ and PM$_{10}$ in May and June were due to stable meteorological conditions. However, the highest hourly PM$_{10}$ concentration occurred in March 9, 2013, probably due to the dust storm in the day (Zheng et al., 2014).

Fig. 3(a) shows monthly variations of PM$_{2.5}$/PM$_{10}$ and PM$_{2.5}$/CO ratios in Zhengzhou from March 1, 2013 to February 28, 2014. The mean value of PM$_{2.5}$/PM$_{10}$ was higher in winter (0.690) because of the increased local emissions from heating and the peak value in October (0.711) was the result of biomass burning (Zheng et al., 2014). PM$_{2.5}$/PM$_{10}$ ratios were lower in March (0.526) and April (0.545) because of the frequent dust storm and the strong winds which increased the concentrations of coarse particles in the air (Zheng et al., 2014). Cheng et al. (2008) reported that aerosols consisted of many coarse particles in spring, probably due to the dust particles transported from northern China. For the whole study period, PM$_{2.5}$ contributed to 61% of PM$_{10}$. The higher abundance of coarse particles in PM$_{10}$ indicated that local dust emissions and regional dust transport may play an important role in the PM$_{10}$ formation (Yan, et al., 2015). The main sources of PM$_{10}$ are from the traffic exhaust, power plants, industrial dust, and energy combustion in Zhengzhou. In addition, sand beach of Yellow River in northern Zhengzhou is the significant source of urban dusts (Du et al., 2012). As shown in de Gouw et al., (2009), one can use the enhancement ratios of the observations to the mixing ratio of an inert trace gas such as CO to account for the effect of emissions and boundary-layer height. In this study, the enhancement of PM$_{2.5}$ to CO ratios was used to further discuss the secondary production of PM$_{2.5}$ (de Gouw et al., 2009; Zhang and Cao, 2015). The average ratios of PM$_{2.5}$/CO in winter (0.047) and summer (0.041) were higher than spring (0.037) and autumn (0.036), suggesting a profound impact of secondary particle formation processes in these two seasons. The intense summer sunlight made emission precursors more readily form secondary particles through a series of photochemical reactions (Wang et al., 2016), while the subsequent secondary PM production because of the increased emissions for heating in winter can cause the enhanced PM$_{2.5}$ concentrations in the atmosphere.

### Diurnal Variations of Air Pollutants

Fig. 4 shows diurnal mean variations of hourly PM$_{2.5}$, O$_3$, PM$_{10}$, SO$_2$, NO$_2$ and CO concentrations in Zhengzhou for different seasons. In general, PM$_{2.5}$, PM$_{10}$, SO$_2$ and NO$_2$ showed significant seasonal variations with the highest in the winter and the lowest in the summer. The maximum level in winter is due to a growing number of anthropogenic activities such as fossil fuel combustion. Primary emissions and secondary production of aerosols with adverse meteorological conditions could also further augment air pollutant concentrations. As can be seen, SO$_2$, NO$_2$ and CO concentrations reached peaks between 9 am to 12 pm, a little earlier than the peak of the PM$_{2.5}$ concentrations (between 10 am to 2 pm), reflecting a significant contribution of primary emissions from automobiles and coal combustion and the subsequent secondary PM production to the enhanced PM$_{2.5}$ concentrations in a day time. The PM$_{2.5}$ concentrations decreased from late afternoon partly due to a combination of the increased PBL and reduced anthropogenic emissions. After 7pm vehicular emission increased and resultantly NO$_2$ concentration can raise the PM$_{2.5}$ level in atmosphere. The stagnant atmospheric conditions could also further contribute to the accumulation of PM$_{2.5}$ in the evening. The lowest O$_3$ level observed around 7 to 9 am is probably
Fig. 3. (a) Monthly mean variations of PM$_{2.5}$/PM$_{10}$ and PM$_{2.5}$/CO ratios, diurnal variations of (b) PM$_{2.5}$/PM$_{10}$ and (c) PM$_{2.5}$/CO ratios for different seasons in Zhengzhou from March 1, 2013 to February 28, 2014.

because of relatively weak solar radiation in the morning. Another reason for the lowest O$_3$ is that it takes some time for NO$_2$ emitted during morning rush hours to form O$_3$. The high negative correlation coefficient (R = –0.604) between O$_3$ and NO$_2$ indicates that O$_3$ was remarkably influenced by the NO$_2$ concentration (Fig. 5(a)) because of the titration of NO from the car emissions (Yu et al., 2006b; Ran et al., 2009; Shan et al., 2009). The highest O$_3$ concentration in late afternoon during 3 pm to 5 pm was mainly caused by high temperature and stronger photochemical effect (Chen et al., 2015; Zhou et al., 2015). Fig. 5(b) shows the positive correlation between O$_3$ and temperature (R = 0.615). The concentrations of O$_3$ kept low at night which is associated with depletion reactions, dilution and dispersion processes. Figs. 3(b) and 3(c) show diurnal variations of PM$_{2.5}$/PM$_{10}$ and PM$_{2.5}$/CO ratios in Zhengzhou from March 1, 2013 to February 28, 2014 for different seasons. The variation patterns of PM$_{2.5}$/PM$_{10}$ ratios showed winter > autumn > summer > spring. The increased emissions from heating sources in winter created more precursors, which further enhanced the PM$_{2.5}$ concentrations during wintertime. The lower PM$_{2.5}$/PM$_{10}$ ratios in spring might be attributed to dust storm in this season. Fig. 3(b) revealed that the peak values of PM$_{2.5}$/PM$_{10}$ occurred in the afternoon (2 pm–4 pm) in all seasons. This was because of the stronger solar radiation and higher temperature accelerated the photochemical
Fig. 4. Diurnal mean variations of air pollutant concentrations in Zhengzhou from March 1, 2013 to February 28, 2014.
Fig. 5. Correlations (a) between daily average O$_3$ and NO$_2$ concentrations, and (b) between daily average O$_3$ concentrations and temperatures in Zhengzhou.

Fig. 3(c) reported that the peak value of PM$_{2.5}$/CO ratio was in the afternoon (1 pm–3 pm) in all seasons, which could also be attributed to the stronger photochemical reactions and secondary PM production. The times of the lower values were consistent with the traffic flow, highlighting the profound influence of traffic emissions.

Case study of a Typical Haze Episode
Characteristics of Air Pollution during the Case Study Period

Above analyses revealed that the PM$_{2.5}$ pollution in Zhengzhou was very severe, especially in winter. To identify the characteristics and origins of haze pollution in Zhengzhou, we conducted a case study covering a heavy haze period during December 11–29, 2013. The average concentration of PM$_{2.5}$ during this period was 160.78 µg m$^{-3}$ and the proportion of days with fairly good air quality was only 26.3%. To analyze the characteristics of haze pollution during this period, we divided the period into 6 events as shown in Fig. 6. Events 1 and 6 were the clean cases with average concentrations of 41.68 µg m$^{-3}$ and 32.81 µg m$^{-3}$, respectively. Events 2, 3, 4, 5 were associated with the haze cases with average concentrations of 177.97 µg m$^{-3}$, 167.01 µg m$^{-3}$, 242.05 µg m$^{-3}$, and 187.39 µg m$^{-3}$, respectively.

During the case study period, PM$_{2.5}$ had the highest correlation with PM$_{10}$ (R = 0.918), suggesting that the sources of PM$_{2.5}$ and PM$_{10}$ were somewhat similar. Generally, NO$_2$ is an indicator of vehicular emissions and SO$_2$ is attributed to industrial and household emissions, whereas O$_3$ is a marker of photochemical reactions (Statheropoulos et al., 1998; Vardoulakis and Kassomenos, 2008). Correlations between gaseous pollutants and particulate matter are commonly used as an indicator for the identification of the PM sources (Juda-Rezler et al., 2011; Dimitriou and Kassomenos, 2013). There was a very strong correlation between PM$_{2.5}$ and NO$_2$ with correlation coefficient of 0.783, followed by CO (R = 0.610), while the correlation coefficient between PM$_{2.5}$ and SO$_2$ was only 0.109. Nitrate and nitrite are typical signs of traffic sources, which are produced by combustion processes and high temperatures in engines. As a result, their concentrations in the air can be largely associated with vehicular emissions (Gilio et al., 2015). Considering that the mobile sources emit high level of CO and NOx but relatively low level of SO$_2$ (Yu et al., 2006b), this suggests that the formation of PM$_{2.5}$ were partly contributed by increasing automotive emissions in Zhengzhou. However, a more detailed explanation about PM$_{2.5}$ source apportionment in Zhengzhou is subject to further studies including more comprehensive observations of chemical components of PM$_{2.5}$ and its precursors as well as modeling effort at multiple levels.

Influence of Meteorological Conditions

Fig. 6 showed consistent changes in relative humidity (RH), visibility and PM$_{2.5}$ concentration: the high PM$_{2.5}$ concentration corresponds to the high RH and low visibility. During December, the decrease of the temperature in China was accompanied by strong winds. This condition may explain high visibility and lower PM$_{2.5}$ concentration in the
Event 1 and Event 6 (Fig. 6). However, the visibility decreased while RH increased in the Event 2. From Events 2 to 5, high pressure and low wind speed led to stable meteorological conditions which favor the air pollutant accumulation and severe haze formation in Zhengzhou. During this period, the average visibility in Zhengzhou was less than 2 km. This is consistent with the finding of Wang et al. (2014a, b) who reported that equal pressure field with high RH was the cause of low visibility and pollutant accumulation during the haze period.
The correlations among PM$_{2.5}$, visibility and meteorological conditions were summarized in Table 1. The results showed that visibility has higher correlation with RH ($R = -0.917$) and wind speed ($R = 0.643$), while PM$_{2.5}$ also has higher correlation with RH ($R = 0.815$) and wind speed ($R = -0.699$). Thus, RH and wind speed were the main meteorological factors influencing both visibility and PM$_{2.5}$ concentrations. Lower wind speeds can reduce the dispersion processes and the higher relative humidity could increase aqueous-phase production of PM, both of which can increase the PM$_{2.5}$ concentration and decrease visibility.

Cluster Trajectory and CWT Analyses

To characterize the general behavior of air masses during the study period and to evaluate the relative contributions by long range transport of the air pollution, 48 h backward trajectories starting at the arrival level of 100 m for the 9 urban monitoring sites in Zhengzhou were calculated during December 11–29, 2013. Fig. 7(a) represents the 48 h back trajectories for the whole period, and Figs. 7(c)–7(h) show the maps of the 48 h back trajectories from events 1 to 6. In Figs. 7(a) and 7(b), five clusters for all data during the whole period were determined by the cluster analysis algorithm, three short distance transport pathways: SE (Southeast) (16.1%), NE (Northeast) (15%), and N (North) (20%), two long distance transport pathways: N–NW (North-Northwest) (43%) and NW (Northwest) (5.9%). Figs. 7(c) and 7(h) indicate that the 48 h back trajectories for the relatively clean air periods (event 1 and event 6) which mainly belongs to N–NW cluster (as shown in Fig. 7(b), the dominant N–NW cluster (43%) originating from low barometric altitude (623.109 hPa) with the height of 3511.269 m) were coming from the regions far away from the receptor site (like Mongolia, and Inner Mongolia) brought the clean air masses to Zhengzhou. Figs. 7(e) and 7(g) indicate that most of the back trajectories were coming from north during the declining period of the PM$_{2.5}$ concentrations. As shown in Fig. 7(d), for the first PM$_{2.5}$ concentration ascending stage (event 2), most of the 48 h back trajectories were coming from northwest of Zhengzhou, such as Yanan and Kaifeng in Shanxi province, and passed through Xinxiang and Kaifeng in Henan province before they finally reached Zhengzhou. Compared to back trajectories in other periods, most of back trajectories in event 4 (the second PM$_{2.5}$ concentration ascending stage with the highest PM$_{2.5}$ concentration of 242.05 µg m$^{-3}$) were from the short pathways (NE (999.312 hPa) and SE (1025.116 hPa) clusters) which brought the heavily-polluted air masses, resulting in heavy PM$_{2.5}$ pollution in Zhengzhou.

To locate the sources contributing to the PM$_{2.5}$ pollution in Zhengzhou, we calculated CWT values in Figs. 8(a)–8(c) for the whole period, event 2 and event 4. Fig. 8(a) shows that the potential pollution sources were located in northeast and southeast of Zhengzhou. Fig. 8(b) indicates that northeast of Zhengzhou such as Puyang and Kaifeng in Henan province led to the ascending stage of PM$_{2.5}$ for the event 2 in Zhengzhou. Fig. 8(c) reveals that southeast of Zhengzhou such as Zhoukou and Xuchang in Henan province were the potential source regions resulting in the PM$_{2.5}$ ascending stage for the event 4 in Zhengzhou. In addition, the local emissions were also an important factor to the haze pollution in Zhengzhou. According to the environment bulletin of Henan province in 2013, SO$_2$ emission was 1.254 million tons, of which industry contributed 1.1027 million tons. Meanwhile, NO$_2$ emission was 1.5656 million tons, including industrial source of 1.0288 million tons, and vehicle emission of 0.5125 million tons in Henan. This means that industry emissions in Henan province may make a significant impact on PM$_{2.5}$ pollution formation in Zhengzhou.

Ground Observations and AOD Analyses over the Region

Fig. 9 gives spatial distributions of the average PM$_{2.5}$ concentrations in China for the periods of December 11–12, December 13–16, December 17–18, December 19–24, December 25–26 and December 27–29, 2013, corresponding with events 1–6, respectively. Fig. 9(a) reveals that higher PM$_{2.5}$ concentrations occurred in the southern China during the event 1. Figs. 9(b)–9(c) show that haze pollution moved to the northern China first and then extended to cover the most cities in China (Figs. 9(d)–9(e)). Zhengzhou city has suffered from severe haze pollution during these four periods until December 27–29 as shown in Fig. 9(f).

Fig. 10 gives the spatial distributions of the daily average AOD data for the region of 100–125 E and 25–45 N from events 1 to 6, respectively. The areas with red color showed the areas with severe haze pollution. Fig. 10 reveals that the haze pollutions were formed and located in the northeast and south of Zhengzhou for the haze events 2 and 4, respectively. The results were consistent with spatial distributions of the average PM$_{2.5}$ concentrations.

CONCLUSION

As one of the most-polluted city in China, Zhengzhou will face major challenges and has a long way to go to meet the proposed daily PM$_{2.5}$ standard. Although Zhengzhou city
Fig. 7. 48 h air mass back trajectories in Zhengzhou for (a) the whole period, (b) the pressure profile of five clusters, (c) event 1, (d) event 2, (e) event 3, (f) event 4, (g) event 5, (h) event 6.
has made significant efforts in alleviating air pollution, the air quality in Zhengzhou is still not much improved so far. To determine the characteristics of air pollution in Zhengzhou, we analyzed surface air pollution observations (PM$_{2.5}$, PM$_{10}$, O$_3$, NO$_2$, CO and SO$_2$) from March 1, 2013 to February 28, 2014 from the nine monitoring stations. The annual average concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, O$_3$ and CO were 97.17 µg m$^{-3}$, 157.22 µg m$^{-3}$, 50.01 µg m$^{-3}$, 53.94 µg m$^{-3}$, 45.21 µg m$^{-3}$ and 2.431 mg m$^{-3}$, respectively. Monthly variations revealed that all pollutants except O$_3$ showed high values in winter months and low values in summer months. The two peaks of PM$_{2.5}$ and PM$_{10}$ concentrations in October and December were mainly attributed to biomass burning and increased coal consumption, respectively. The O$_3$ concentrations revealed the opposite monthly variation pattern with peak value in August due to higher temperature and stronger solar radiation. The diurnal variations showed that PM$_{2.5}$ concentration variations were consistent with the traffic flow. The lowest values of PM$_{2.5}$/PM$_{10}$ and PM$_{2.5}$/CO occurred in the afternoon probably because of the stronger photochemical reactions.

The results of the case study indicated that meteorological conditions were the important factors for the PM$_{2.5}$ pollution formation in Zhengzhou. In addition to the local emissions, northeast and southeast of Zhengzhou such as Puyang, Kaifeng, Zhoukou, and Xuchang in Henan province were the most potential source regions for the haze formation in Zhengzhou. The characteristics analyses of air pollution in Zhengzhou showed that the air pollution was associated with primary emissions (such as emissions from automobiles and coal combustions), secondary production of aerosols, stagnant weather and regional transport. Therefore, it is essential to reduce primary emissions from cars and coal combustions, implement air pollution control not only at a local level, but also for all surrounding areas, especially for the regions in the northeast and southeast of Zhengzhou. Since the results of this work can only determine the potential sources responsible for the haze formation in Zhengzhou in terms of transport, there is a need to use 3-D air quality models to do further study.
Fig. 9. Average PM$_{2.5}$ concentrations for the periods of (a) event 1, (b) event 2, (c) event 3, (d) event 4, (e) event 5, (f) event 6.
Fig. 10. Observations of AOD at 550 nm from the MODIS for the periods of (a) event 1, (b) event 2, (c) event 3, (d) event 4, (e) event 5, (f) event 6.

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