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Article *in* Atmospheric Pollution Research · September 2015

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A heavy haze episode in Beijing in February of 2014: Characteristics, origins and implications

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ABSTRACT

More than half Chinese cities are suffering from severe air pollution due to the rapid development of industry and urbanization. Beijing, as a political and cultural center of China, has frequently suffered from severe haze. However, the precise sources of air pollution in Beijing still remain uncertain. In this study, the observational data ($PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2) at ten monitoring stations from February 8 to 28, 2014, in Beijing were used to analyze air pollution. The satellite observations for aerosol optical thickness were also used. Backward trajectory model and receptor models were used to identify the sources of air pollution in Beijing. On the basis of $PM_{2.5}$ concentrations, we separated the whole data into three categories: relatively clean air ($PM_{2.5}$ concentrations less than 75 μg m^{-3}), haze ($PM_{2.5}$ concentrations greater than 75 μg m^{-3} but less than 200 μg m^{-3}) and heavy haze ($PM_{2.5}$ concentrations greater than 200 μg m^{-3}). The results show that the average concentrations of $PM_{2.5}$ are 29.5 μg m^{-3}, 136.6 μg m^{-3} and 311.2 μg m^{-3} for relatively clean air, haze and heavy haze cases, respectively. The back trajectory cluster analysis reveals that the predominant clusters are east and south for the heavy haze case. The results of the receptor models show that for the haze case, pollutants mainly originated from south of Beijing such as Dezhou, Liaocheng and Heze in Shandong province, while for the heavy haze case, pollutants were mainly from southwest of Beijing such as Baoding, Hengshui and Handan in Hebei province. These results indicate that the emissions in the surrounding provinces made a significant contribution to Beijing's air pollution. Thus, it is necessary to implement air pollution control for all surrounding areas, especially for the industrial zones in the south/southwest regions of Beijing.

Keywords: *Air pollution, haze, trajectories model, cluster analysis, sources*

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Article History:
Received: 20 December 2014
Revised: 15 March 2015
Accepted: 15 March 2015

doi: 10.5094/APR.2015.096

1. Introduction

As a developing country, China has achieved rapid economic development over the past few decades. However, its success was accompanied by environmental deterioration, including air, water and soil pollutions. In recent years, air pollution has become the most serious environmental problem in China (Chan and Yao, 2008). Researches show that more than two–thirds of urban areas in China do not meet China's national ambient air quality standards (secondary daily national air quality standard for $PM_{2.5}$ is 75 μg m^{-3}) (Hao and Wang, 2005; Shao et al., 2006). Although many megacities in the world have also suffered from air pollution, the composition of air pollution in China is particularly complicated. Coal is a major source of energy in China, accounting for about 70% of the total energy consumption. Emissions from coal combustion are the main cause of China's air pollution (Hao et al., 2007; Chan and Yao, 2008). With rapidly increasing in vehicle numbers, vehicle emissions are becoming important for urban pollution (Hao et al., 2007). The source of air pollution in Chinese megacities has gradually shifted from conventional coal combustion to a mixture of coal combustion and vehicle emissions. One of the major air pollutants is particulate matter (PM), particularly fine particles ($PM_{2.5}$) (i.e., PM with an aerodynamic diameter less than 2.5 μm), which is mostly responsible for the formation of the regional haze (the day with visibility <10 km under the conditions of 80 % relative humidity (RH)) in China. In most Chinese cities, $PM_{2.5}$ concentrations are much higher than the World Health Organization (WHO) Air Quality Guidelines of 10 μg m^{-3} (annual average) and 25 μg m^{-3} (daily average) (WHO, 2005). Severe air pollution affects not only human health, regional and global climates, but also the economic development and social progress (Yu, 2000; Yu et al., 2000; Yu et al., 2001a; Yu et al., 2001b; Shao et al. 2006; Chan and Yao, 2008; Zhang, 2008; Yu, 2014; Yu et al., 2014a; Yu et al., 2014b; Yu et al., 2014c). Although many studies about the air pollution and haze–fog in China have been carried out, the reasons of heavy haze formation for many cities still remain an issue of uncertainty. Air pollution problems in China's megacities will continue to be an important topic of environmental issues in the coming decades.

Beijing, the political and cultural center of China, is one of the largest cities in the world and also is the China's second most populous city with an urban population 20.6 million over an area of about 16 410 square kilometers. $PM_{2.5}$ in Beijing is abnormally elevated, and often rising to more than 100 μg m^{-3}. According to the government statistics, the $PM_{2.5}$ concentrations in only eight days are less than 75 μg m^{-3} (National Air Quality Secondary Standard) in January 2013. The latest results show that the severe haze pollution episodes in megacities were driven to a large extent by secondary aerosol formation, which contributed 50% of $PM_{2.5}$ in Beijing (Huang et al., 2014). On the other hand, Guo et al. (2014) found that photochemical oxidation of VOCs and NO_X from urban traffic emissions and SO_2 from regional industrial sources are primarily responsible for the periodic cycles of severe haze episodes in Beijing on the basis of comprehensive atmospheric measurements from 25 September to 14 November 2013. In addition, Beijing is a city sensitive to regional transport of aerosols from its surrounding provinces. According to Bergin et al. (2005), some pollutants can be regionally transported over hundreds or thousands of kilometers, long enough to cross provincial, national, and even continental boundaries. Due to the unique topography and meteorology, atmospheric pollutants from the surrounding

areas are also significantly important to the air pollution formation in Beijing (Chen et al., 2007). Wang et al. (2010) pointed out that the most serious PM_{10} pollution in Beijing can be attributed to the pollution emissions in the southwestern regions. The result of $PM_{2.5}$ source apportionment shows that the major aerosol components in Beijing may primarily come from the southern region (Zhang et al., 2013).

In recent years, air mass trajectory model, cluster analysis, potential source contribution function (PSCF) and concentration weighted trajectory (CWT) methods have been widely used to assess the prevailing transport pathways and the source regions of air pollutants (Wang et al., 2004; Wang et al., 2010; Liu et al., 2013; Zhang et al., 2013; Yu et al., 2014c). Beijing had suffered from severe haze from February 21 to 27, 2014, that is the longest time of heavy haze after carrying out air quality monitoring under new air quality standard since January 1, 2013. In this work, we analyzed the air pollution in Beijing from February 8 to February 28, 2014, using the surface and satellite observational data. Meanwhile, the air mass back trajectory and receptor models (PSCF and CWT) were used to study the possible impact of local and transport pollutant sources on the formation of haze in Beijing before and during the haze episode.

2. Methodology

2.1. Observational data

Hourly air pollutants ($PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2) at 10 urban monitoring stations (Wanshouxigong (39.87°N, 116.37°E), Changpinzhen (40.20°N, 116.23°E), Nongzhanguan (39.97°N, 116.47°E), Tiantan (39.87°N, 116.43°E), Guanyuan (39.94°N, 116.36°E), Haidianquwanliu (39.99°N, 116.315°E), Dongsi (39.95°N, 116.43°E), Gucheng(39.93°N, 116.23°E), Shunyixincheng (40.1438 N, 116.72°E), Aotizhongxin (40.00°N, 116.41°E)) in Beijing were measured with the standard methods (CNEMC, 2013). The China National Environ-mental Monitoring Center (CNEMC) has started to release the real–time hourly concentrations of $PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2 at 496 national monitoring stations in 74 major cities in China since January 2013. These 10 urban monitoring stations in Beijing belong to part of them. The more detailed information about the observational data can be found in the website of Ministry of Environmental Protection in China (ARL, 2015). In addition, the aerosol optical depth (AOD) data at 550 nm obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) was used in this study. MODIS instrument aboard the Terra (EOS AM) spacecraft passes from north to south across the equator in the morning. Because the effective satellite daily data over the study region are relatively scarce, we mainly elected MOD08_D3 data (Level–3 data) with a 1° spatial resolution from February 8 to 28, 2014.

2.2. Air mass back trajectory calculation, clustering analysis, PSCF and CWT

Following Yu et al. (2014c), the 48 h back trajectories starting at the arrival level of 100 m from the 10 urban monitoring sites in Beijing were calculated with the NOAA HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php) to study the possible impact of local and transport sources on the formation of haze in Beijing during the study period (February 8 to February 28, 2014). Since the 10 monitoring sites are very close, the trajectory clusters method is used for all sites as a whole. In this work, we used the angular distance to do cluster analysis. The method used to calculate the mean angle distance between two trajectories was adapted from Sirois and Bottenheim (1995). The NCEP/FNL (National Centers for Environmental Prediction, Final Analyses) fields obtained from NOAA available every 3 h with a spatial resolution of 0.5×0.5 were used as meteorological data input to the model. Based on the 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) (16:00, 19:00, 22:00, 01:00, 04:00, 07:00, 10:00 and 13:00 UTC, respectively).

Based on the results of the HYSPLIT model, the PSCF method can be used to identify the probable locations of emission sources which affect pollutant loadings at the receptor site (Hsu et al., 2003). The PSCF values for the grid cells in the study domain are calculated by counting the trajectory segment endpoints that terminate within each cell at the measurement time. The PSCF value for the cell (*i,j*) is defined as (Ashbaugh et al., 1985; Wang et al., 2009):

$$PSCF_{ij} = \frac{m_{ij}}{n_{ij}} \quad (1)$$

where, n_{ij} represents total number of the trajectory segment endpoints at the grid cell (*i,j*), and m_{ij} is the number of the trajectory segment endpoints at the grid cell (*i,j*) with $PM_{2.5}$ concentrations higher than an arbitrarily set criterion. $PM_{2.5}$ criterion is set to 75 μg m^{-3} for the polluted concentration in this study. The cells with high PSCF values are indicative of the areas that have high potential contributions to the high pollutant concentrations at the receptor site. A limitation of the PSCF method is that grid cells may have the same PSCF value when the pollutant concentrations are only slightly higher or extremely higher than the criterion. To compensate the limitation, a concentration weighted trajectory (CWT) method was used to calculate the trajectory weighted concentration. The CWT method calculated the average weighted concentration C_{ij} for the grid cell (*i,j*) as follows (Hsu et al., 2003; Wang et al., 2009):

$$C_{ij} = \frac{1}{\sum_{l=1}^{M} T_{ijl}} \sum_{l=1}^{M} C_l \, T_{ijl} \quad (2)$$

where, *l* and *M* represent the index and total number of the trajectories, respectively. C_l is the concentration observed at the receptor site on the arrival of trajectory *l*. T_{ijl} is the time spent in the grid cell (*i,j*) by trajectory *l*. A high C_{ij} value implies that the air parcels traveling over the grid cell (*i,j*) would be associated with high polluted values at the receptor site.

3. Results and Discussion

3.1. Characteristics of the heavy haze episode in Beijing

Extremely severe and persistent haze has frequently occurred in Beijing since 2012, and concentrations of $PM_{2.5}$ on hourly average are often record–breaking. Figure 1 shows the temporal variations of hourly $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3 observed at the ten sites in Beijing from February 8 to 28, 2014. The results at these 10 sites were analyzed together as a whole because the $PM_{2.5}$ concentrations at the ten monitoring sites are close as shown in Figure 1. Generally, the concentrations of air pollutants like $PM_{2.5}$, PM_{10}, SO_2, CO and NO_2 had the same trends of change during this period, with the exception of O_3. The O_3 concentrations show obvious diurnal variations for the whole period with values below 100 μg m^{-3}, much lower than the China hourly national air quality standard of 200 μg m^{-3}. The SO_2, NO_2 and CO concentrations during this period ranged from 1 to 207 μg m^{-3}, 2 to 263 μg $m^{-3}$and 0.1 to 9.8 mg m^{-3}, respectively, which are much lower than the corresponding hourly national air quality standard (500 μg m^{-3} for SO_2, 200 μg m^{-3} for NO_2 and 10.0 mg m^{-3} for CO) in most of the times. The NO_2 concentrations with values higher than 200 μg m^{-3} are mainly occurred during the heavy haze period from 24 to 27 February. Because SO_2, NO_2 and CO are emitted directly from biomass, fuel and coal burning, their concentrations can be affected more significantly by the local sources.

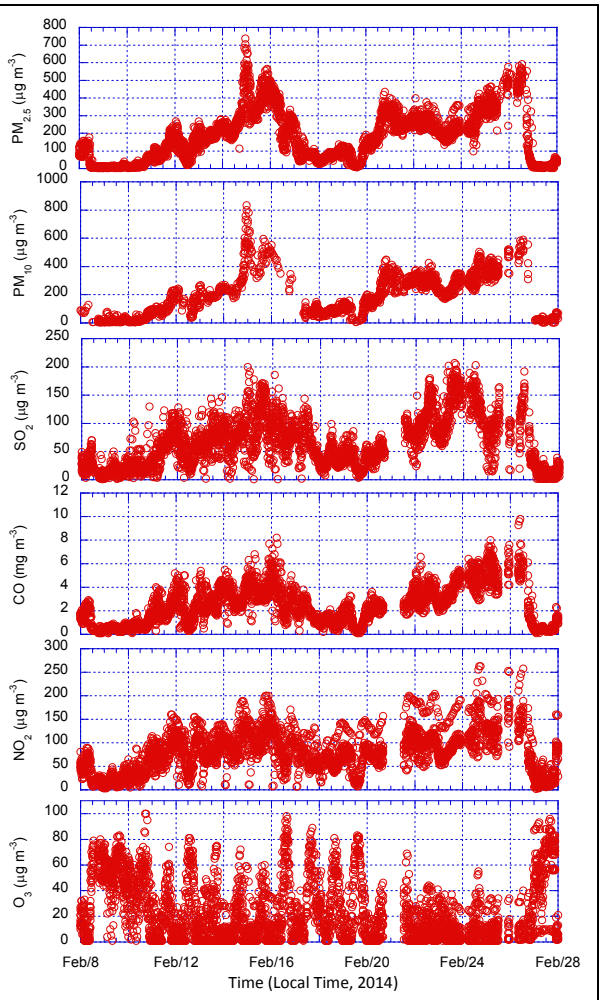

Figure 1. *Time series of hourly concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3 from 8 to 28 February, 2014, at 10 sites in Beijing.*

For $PM_{2.5}$ and PM_{10} concentrations, there are even more obvious trends of changes during the period from 8 to 28 February, 2014. Figure 1 shows that $PM_{2.5}$ concentrations are higher than 200 μg m^{-3} in most of time for two periods: 12 to 17 February and 20 to 27 February, 2014. PM_{10} concentrations had the same patterns like $PM_{2.5}$. Note that there are less observational data of PM_{10} at all sites from 8 to 28 February relative to those of $PM_{2.5}$ because of instrumentation failures as shown in Figure 1. Since the National Air Quality Secondary Standard for $PM_{2.5}$ is 75 μg m^{-3}, we separated the whole data into three categories on the basis of $PM_{2.5}$ concentrations: relatively clean air ($PM_{2.5}$ concentrations less than 75 μg m^{-3}), haze ($PM_{2.5}$ concentrations greater than 75 μg m^{-3} but less than 200 μg m^{-3}) and heavy haze ($PM_{2.5}$ concentrations greater than 200 μg m^{-3}). Note that since $PM_{2.5}$ concentrations are often above 200 μg m^{-3} during the severe haze periods in Beijing, the results for the cases with $PM_{2.5}$>200 μg m^{-3} are analyzed as a separated case in this study. For the relative clean air period, all pollutant concentrations are relatively low with the average concentration of $PM_{2.5}$ of about 29.5 μg m^{-3}. The average concentrations of $PM_{2.5}$ are 136.6 μg m^{-3} and 311.2 μg m^{-3} for the haze and heavy haze periods, respectively. For the heavy haze period, the highest concentration of $PM_{2.5}$ is as high as 700 μg m^{-3} on February 15, which is record–breaking.

Figure 2 shows the spatial distributions of the average AOD values at 550 nm over the Eastern China for the periods of 8 to 14 February, 15 to 17 February, 18 to 20 February, 21 to 27 February and 8 to 27 February, 2014. The evolution of AOD in Figure 2 shows movements of the heavy haze over China for the whole study period and is consistent with variations of $PM_{2.5}$ observed in Beijing in Figure 1. It is of interest to note that most of the heavy haze pollution were located over the southern and central parts of China (Figure 2a) during the period of 8 to 14 February, and moved to northeast for the period of 15 to 17 February (see Figure 2b). For the period of 21 to 27 February, most of the heavy haze pollution already moved offshore and were located at the Bohai Sea and Yellow Sea (see Figure 2d).

3.2. Trajectory clustering

In Figure 3a, five clusters for all data during the whole period were produced by the clustering algorithm: S (South), E (East), N (North), N–NW (North–Northwest) and NW (Northwest). The back trajectories for the relatively clean air, haze and heavy haze periods, are also shown in Figures 3b, 3c and 3d, respectively. Table 1 summaries the percentages of trajectories for each trajectory cluster for four cases (i.e., whole period from 8 to 28 February, relatively clean air period, haze period and heavy haze period), corresponding mean concentrations of $PM_{2.5}$ and mean wind speeds. Table 1 also lists the results for the polluted cases when $PM_{2.5}$ criterion is set to 75 μg m^{-3} (the Class II Chinese $PM_{2.5}$ standard). As shown in Figure 3 and Table 1, the main characteristics of air pollution sources are different for the different periods. For the relatively clean air period, the 48 h back trajectories mainly came from the very far away regions like Xinjiang province, Inner Mongolia and Mongolia. However, the 48 h back trajectories mainly came from local areas and nearby provinces like Hebei, Shandong and Liaoning provinces for the haze and heavy haze periods. According to the cluster analysis (see Table 1), the trajectory clusters for the whole period are dominated by cluster S, accounting for 42.5%, and the E, N, N–NW and NW clusters accounted for 30.1%, 16.1%, 7.0% and 3.6%, respectively. For the relatively clean period with $PM_{2.5}$<75 μg m^{-3}, the predominant cluster is N (74.2%) which brings fresh clean air from Inner Mongolia and Mongolia areas. It is of interest to note that the cluster NW also brings fresh clean air from Xinjiang province for the relatively clean period in Beijing. Table 1 shows that the mean wind speeds of N and NW clusters for the relatively clean period are 9.1 and 15.4 m s^{-1}, respectively, indicating the effects of fast air masses from the very far away clean regions. For the very heavy haze period with $PM_{2.5}$>200 μg m^{-3}, all back trajectories came from either south (S) or east (E) clusters associated with the very slow air masses which have the mean wind speeds <2.0 m s^{-1} as summarized in Table 1. The results indicate that the pollution sources in the south and east, especially in the south areas of Beijing, were mainly responsible for the heavy haze formation in Beijing. For the haze period with 75 μg m^{-3}<$PM_{2.5}$<200< μg m^{-3}, the predominant clusters are still S (35.8%) and E (43.5%) with some contributions from the N–NW (16.4%) and N (4.3) clusters as shown in Figure 3c. Figure 3 and Table 1 clearly indicate that the mean wind speeds for the haze period are between those for the relatively clean and very heavy haze periods. This indicates that air masses from the N and N–NW clusters can be also polluted if the mean wind speeds are less than 4 m s^{-1}, while air masses from the S and E clusters can be also just polluted instead of heavily polluted if the wind speeds are somehow large as shown in Figure 3 and Table 1.

3.3. Source contributions from PSCF and CWT analyses

Figure 4 shows the distributions of the PSCF values of $PM_{2.5}$ and NO_2 in Beijing for the haze and heavy haze periods. The PSCF values were calculated by using the Class II Chinese standard ($PM_{2.5}$<75 μg $m^{-3}$and NO_2<80 μg m^{-3}) as criterions. In general as shown in Figure 4, the cells with high PSCF values were located mainly in the south and southwest of Beijing, such as Baoding, Shijiazhuang, Cangzhou, Hengshui and Handan in Hebei province, Dezhou, Liaocheng and Heze in Shandong province for both

periods. These potential sources are most likely leading to the high $PM_{2.5}$ and NO_2 concentrations in Beijing. For the haze period, the potential sources in the areas such as Dezhou, Liaocheng and Heze in Shandong province are most likely leading to high $PM_{2.5}$ and NO_2 concentrations in Beijing (see Figure 4a and 4b). Meanwhile, Baoding, Shijiazhuang and Hengshui areas may also have a great contribution to the Beijing's high $PM_{2.5}$ concentration during the haze period. Since the $PM_{2.5}$ concentrations were higher than 200 μg m^{-3} during the heavy haze period, almost all the PSCF values are 1.0 as shown in Figure 4c. For the heavy haze period, the potential source areas of regions, including Baoding, Cangzhou, Hengshui and Handan in Hebei province, Dezhou in Shandong province, and Tianjin, are most likely leading to the high $PM_{2.5}$ and NO_2 concentrations in Beijing (see Figure 4c and 4d). Note that Jinzhou in Liaoning province is also probably a potential source area for the heavy haze period.

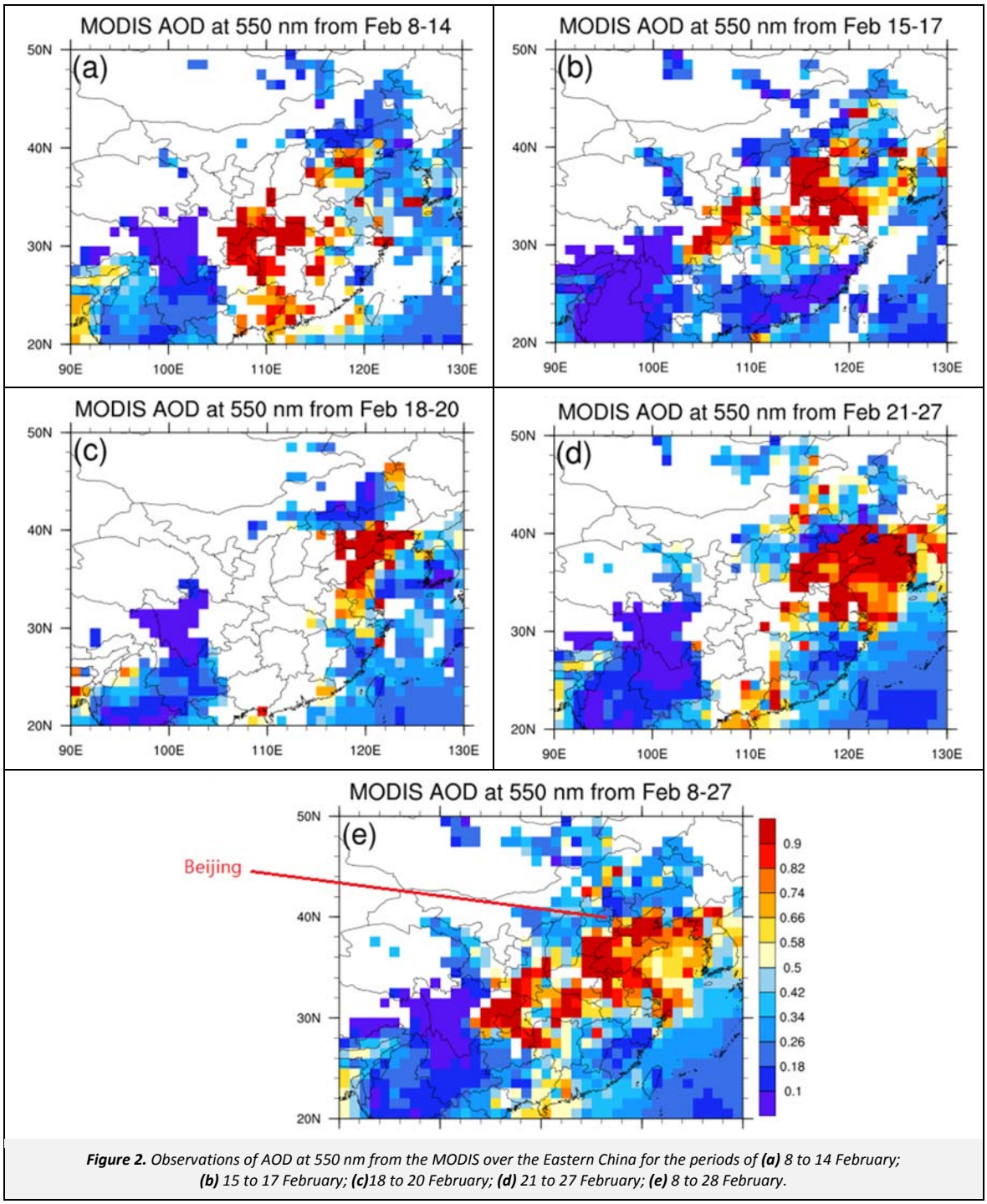

Figure 2. *Observations of AOD at 550 nm from the MODIS over the Eastern China for the periods of* ***(a)*** *8 to 14 February;* ***(b)*** *15 to 17 February;* ***(c)****18 to 20 February;* ***(d)*** *21 to 27 February;* ***(e)*** *8 to 28 February.*

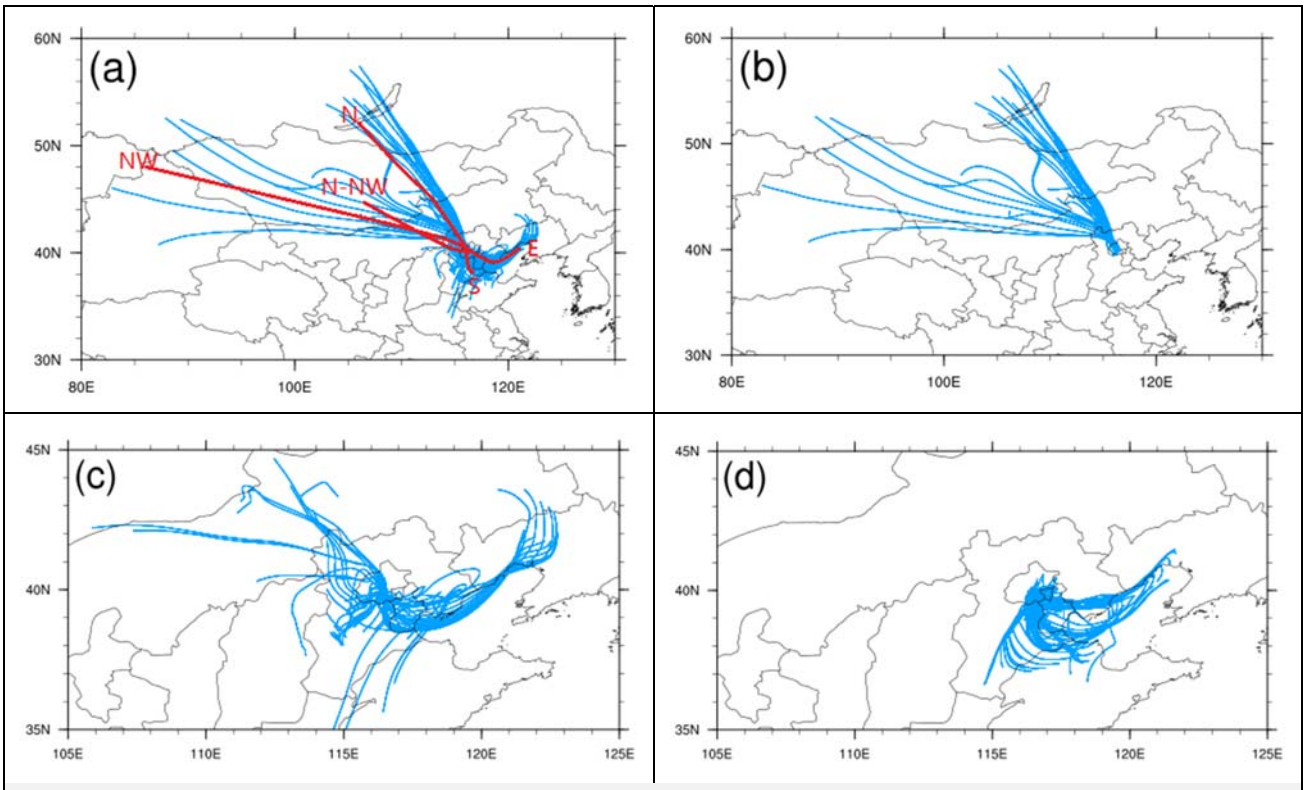

Figure 3. *Cluster analysis of the 48–h air mass back trajectories starting at 100 m in Beijing from February 8 to 28, 2014.* ***(a)*** *All back trajectories for the whole period from February 8 to 28. The five transport pathways (clusters) are determined: S (South), E (East), N (North), NW (Northwest) and N–NW (North–Northwest);* ***(b)*** *All back trajectories for the relatively clean cases ($PM_{2.5}$<75 μg m^{-3});* ***(c)*** *All back trajectories for the haze case ($PM_{2.5}$≥75 μg m^{-3} but $PM_{2.5}$<200 μg m^{-3});* ***(d)*** *All back trajectories for the heavy haze case ($PM_{2.5}$≥200 μg m^{-3}).*

Table 1. *Mean concentrations of $PM_{2.5}$ percentages of trajectories for each trajectory cluster for the whole period (February 8 to 28, 2014) and three sampling periods (relatively clean air:$PM_{2.5}$<75 μg m^{-3}; haze: $PM_{2.5}$≥75 μg m^{-3} but $PM_{2.5}$<200 μg m^{-3}; heavy haze: $PM_{2.5}$≥200 μg m^{-3}). Values in the parentheses are number of back trajectories*

		Percent (%)	Mean $PM_{2.5}$ (μg m^{-3})	Polluted Percent (%)	Polluted Mean $PM_{2.5}$ (μg m^{-3})	WS (m s^{-1})
All Data for the Whole Period	N	16.1 (241)	15.93	0.1 (1)	138	8.7
	N–NW	7.0 (105)	64.16	2.9 (30)	101	4.2
	NW	3.6 (54)	18.33	0.1 (1)	233	15.4
	E	30.1 (458)	170.91	36.7 (373)	197.3	1.3
	S	42.5 (635)	268.4	60.2 (612)	276.41	2
Clean	N	74.2 (219)	15.26	0	0	9.1
	N–NW	7.5 (22)	54.32	0	0	5.6
	NW	18.3 (54)	18.33	0	0	15.4
Haze	N	4.3 (22)	22.55	0	0	4
	N–NW	16.4 (83)	66.77	9.0 (29)	101.8	3.8
	E	43.5 (220)	95.31	41.9 (135)	120.61	1.3
	S	35.8 (181)	142.57	49.1 (158)	155.28	2.5
Heavy Haze	E	34.4 (238)	318.56	34.4 (238)	318.56	1.3
	S	65.6 (454)	291.81	65.6 (454)	291.81	1.8

Figure 5 shows the distributions of the CWT values of $PM_{2.5}$ and NO_2 for the whole, relatively clean air, haze and heavy haze periods. According to the CWT analyses, the CWT values can indicate the relative contributions of each potential source to the high concentration values at the receptor site. Figures 5a and 5b show that the air masses primarily came from Inner Mongolia and Mongolia with the low $PM_{2.5}$ and NO_2 concentrations during the relatively clean air period. The distributions of the CWT values in Figure 5c and 5d indicate that during the haze period, the sources affecting a high $PM_{2.5}$ and NO_2 concentrations in Beijing are mainly located in the south of Beijing, such as Dezhou, Liaocheng and Heze in Shandong province. On the other hand, the potential source areas are primarily located in the southwest regions of Beijing like Baoding, Hengshui and Handan in Hebei province during the heavy haze period (Seen in Figure 5e and 5f). These potential sources lead to $PM_{2.5}$ concentration exceeding

200 μg m^{-3}, and NO_2 concentration exceeding 100 μg m^{-3} in Beijing. The results of Figure 5c and Figure 5e clearly show that the pollutants transported to Beijing are primarily originated from the south and southwest of Beijing. Figure 6 shows the results of CWT analyses for SO_2 for the haze and heavy haze periods. As can be seen in Figure 6, the CTW results of SO_2 are similar to those of NO_2. For the haze period, the sources affecting Beijing's SO_2 are mainly located in Dezhou, Liaocheng and Heze in Shandong province, while during the heavy haze period, the sources affecting Beijing's SO_2 are mainly located in Baoding, Hengshui and Handan in Hebei province. The pollutants from Jinzhou in Liaoning province also have a significant impact on the distributions of Beijing's SO_2. On the other hand, Guo et al. (2014) reported that the large secondary formation, which originates from the photochemical oxidation of VOCs and NO_X from urban traffic emissions and SO_2 from regional industrial sources, is primarily responsible for Beijing's severe $PM_{2.5}$ events. The results in this work in Figure 5 are somewhat different to the analyses of Guo et al. (2014) for $PM_{2.5}$ and NO_2. Our results in Figure 6 confirm the finding of Guo et al. (2014) about the regional transport effects on SO_2 concentrations in Beijing.

3.4. Analysis of correlations among $PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2

To investigate the relationships among $PM_{2.5}$, PM_{10}, O_3, NO_2, CO and SO_2, Pearson correlation coefficients are calculated on the basis of the hourly concentrations for each species and are listed in Table 2. The results for the coarse particle mass (PM_{10}–$PM_{2.5}$) are also listed in Table 2. Table 2 shows that there is very strong correlation between PM_{10} and $PM_{2.5}$ with correlation coefficient (r) of 0.98. This is because of the fact that 88% of PM_{10} (mean concentration: 206.70±147.78 μg m^{-3}) is $PM_{2.5}$ (mean concentration: 182.47±135.43 μg m^{-3}) in Beijing, while coarse particles (mean concentration: 24.23±27.67 μg m^{-3}) only contribute 12% of PM_{10}. This is consistent with the results at the Fresno Site of California where the coarse particles also only contributed 11% to PM_{10} for a wintertime $PM_{2.5}$ episode (Watson and Chow, 2002). Since coarse particles are from the dust–producing activities such as wind on soils, traffic on the streets and constructions, the results here indicate that the dust–producing activities are not the main sources of $PM_{2.5}$ in Beijing as supported by the very weak correlation between the coarse particles and $PM_{2.5}$ (r=0.36, Table 2).

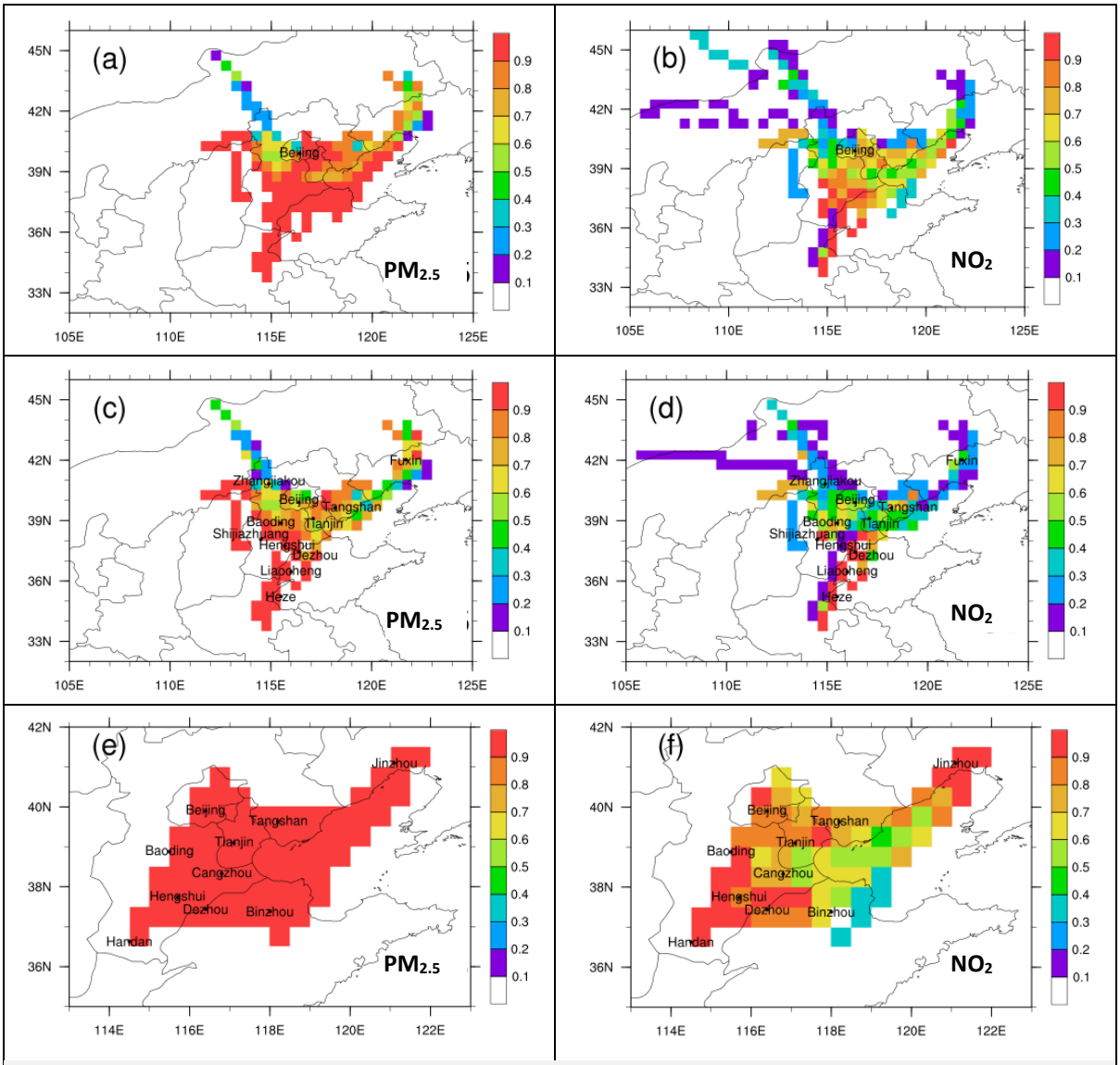

Figure 4. *Potential source contribution function (PSCF) maps for $PM_{2.5}$ and NO_2: **(a)** and **(b)** for all data; **(c)** and **(d)** for the haze period; **(e)** and **(f)** for the heavy haze period.*

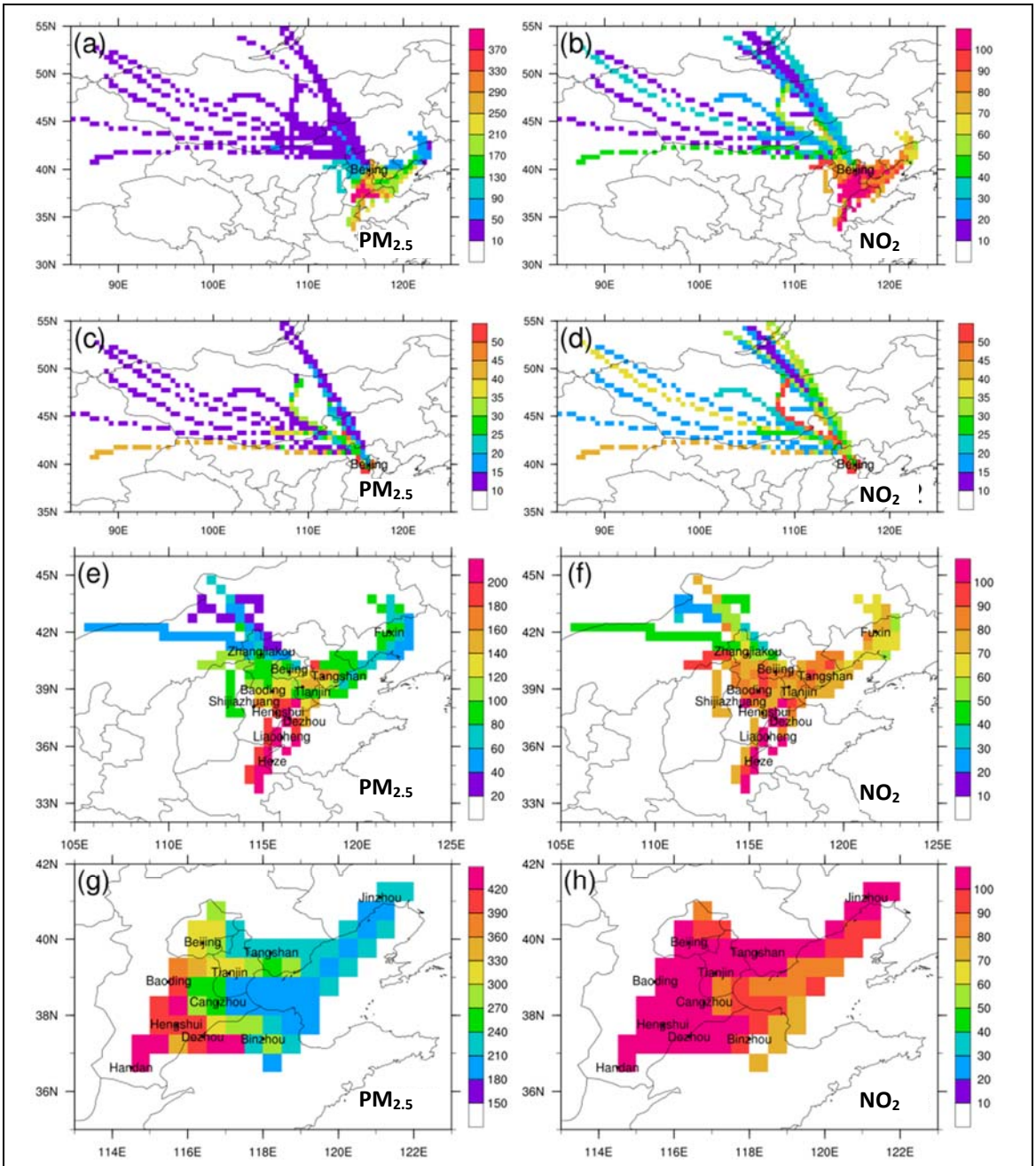

Figure 5. *Concentration–weighted trajectory (CWT) method analysis maps (unit is μg m^{-3} for both $PM_{2.5}$ and NO_2) for $PM_{2.5}$ and NO_2: **(a)** and **(b)** for all data; **(c)** and **(d)** for the relatively clean period; **(e)** and **(f)** for the haze period; and **(g)** and **(h)** for the heavy haze period.*

Table 2. *Correlation coefficients among different species for the whole study period*

	$PM_{2.5}$	PM_{10}	PM_{10}–$PM_{2.5}$	SO_2	NO_2	CO	O_3
$PM_{2.5}$	1.00						
PM_{10}	0.98	1.00					
PM_{10}–$PM_{2.5}$	0.36	0.52	1.00				
SO_2	0.69	0.74	0.61	1.00			
NO_2	0.76	0.81	0.46	0.67	1.00		
CO	0.85	0.88	0.51	0.75	0.83	1.00	
O_3	–0.50	–0.56	–0.33	–0.47	–0.70	–0.61	1.00

The mobile sources (or urban plumes) emit high level of CO and NO_X but relatively low level of SO_2, while the point sources (mainly coal–burning) from power plants emit high level of SO_2 and NO_X but relatively low level of CO (Yu et al., 2006). It is of interest to note that $PM_{2.5}$ has the strongest correlation with CO (r=0.852), followed by NO_2 (r=0.763) and SO_2 (r=0.691) as shown Table 2. This suggests that $PM_{2.5}$ formation is affected by the sources similar to those of CO. Since CO is a long–lived tracer of human activity with well–known sources such as combustion, industry, mobile, and oxidation of hydrocarbons (Yu et al., 2006), this means that $PM_{2.5}$ formation is also the results of different sources including combustion, industry, mobile, and oxidation of hydrocarbons. The sources from both power plants and mobiles make a significant contribution to the formation of $PM_{2.5}$ in Beijing. On the other hand, the negative correlations between O_3 and other species ($PM_{2.5}$, PM_{10}, NO_2, CO and SO_2) indicate that the sources of O_3 are different from other species. The good positive correlation between NO_2 and $PM_{2.5}$ (r=0.763) confirms that the high $PM_{2.5}$ concentrations were accompanied with the high NO_X concentrations in Beijing. The significant negative correlation between O_3 and NO_2 (r=–0.70) also confirms the destruction of O_3 by NO_X. Lin et al. (2011) found that the destruction rate of O_3 by NO in the Beijing urban area was about 33 ppbv h^{-1}.

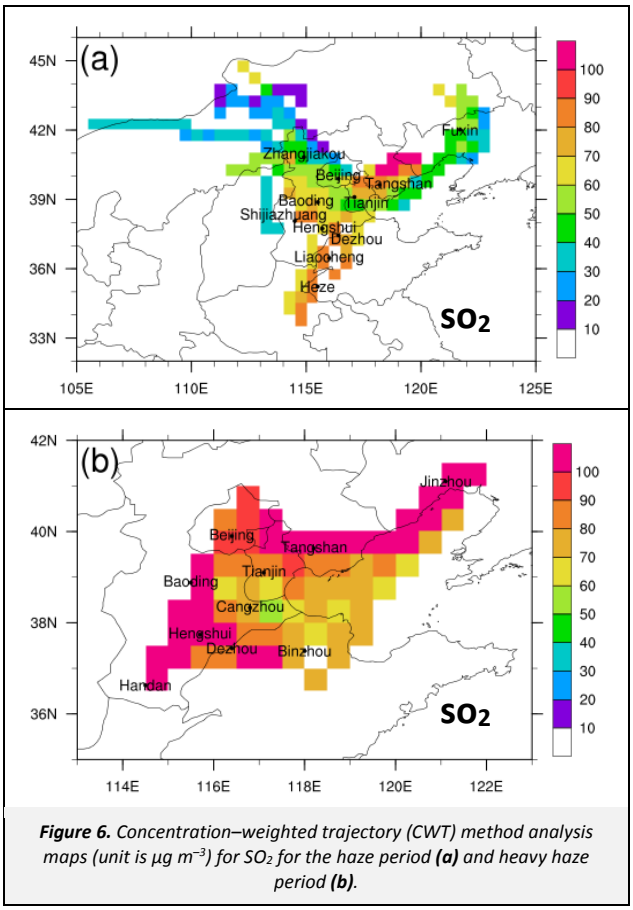

Figure 6. *Concentration–weighted trajectory (CWT) method analysis maps (unit is μg m^{-3}) for SO_2 for the haze period* ***(a)*** *and heavy haze period* ***(b)****.*

3.5. Control strategy implication for haze in Beijing

The results in the above analyses show that the crucial factors for determining the high $PM_{2.5}$ concentrations and haze formation in Beijing are the air pollution transport from the industrial zones in the south/southwest regions of Beijing, such as Dezhou, Liaocheng and Heze in Shandong province, Baoding, Shijiazhuang, Hengshui and Handan in Hebei province. To improve air quality in Beijing during the Asia–Pacific Economic Cooperation (APEC) conference held from November 5 to 11, 2014, Beijing and its neighboring regions (including Tianjin and four provinces (Hebei, Shandong, Inner Mongolia, and Shanxi)) imposed emergency restrictions with a special air pollution control plan (CIBN, 2014). These included extra holidays for public–sector employees, the odd–even license number driving rules, and suspension of emission–heavy production in factories. All the joint efforts were expected to cut emissions of air pollution by at least 30%. As reported by Xinhua agency (CIBN, 2014; CNY, 2014), the cities participating this special air pollution control plan include eight cities (Shijiazhuang, Langfang, Baoding, Xingtai, Handan, Tangshan, Cangzhou, Henshui) in Hebei province, five cities (Ji'nan, Zibo, Dongying, Dezhou, Liaocheng, Binzhou) in Shandong province, three cities (Datong, Shuozhou, Taiyuan) in Shanxi province, and two cities (Baotou, Hohhot) in Inner Mongolia. Many cities imposed most stringent emergency response measures by strengthening their efforts to cut emissions. The tough emissions–reduction measures and favorable meteorological conditions in the region resulted in the blue sky in heavily polluted Beijing during the APEC period, "APEC blue", a term coined by some Chinese netizens. Our results are consistent with those cities imposing emergency restrictions with a special air pollution control plan to ensure clean air in Beijing during the APEC period. The air quality data released by Beijing Municipal Environmental Protection Bureau (Chinadaily, 2014) showed that the daily mean $PM_{2.5}$, PM_{10}, SO_2, NO_2 during the APEC period concentrations were 43, 62, 8 and 46 μg m^{-3}, respectively, and decreased by 55, 44, 57, and 31%, respectively, when compared with the same period last year. The emissions of SO_2, NO_X, PM_{10}, $PM_{2.5}$ and VOCs in Beijing were reduced by 54, 41, 68, 63 and 35%, respectively (Netease, 2014). Success of cutting emissions for the APEC meeting duration has spurred confidence that clean air is attainable and will prompt more measures to curb air pollution. The results also show that reducing emissions and air pollution in the region as a whole is key to ensuring blue skies and good air quality in Beijing.

4. Conclusions

More than half Chinese cities are suffering from severe air pollution due to the rapid development of industry and urbanization. Beijing, as a political and cultural center of China, has frequently suffered from severe haze. In this study, based on the surface observations ($PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3) at the 10 urban monitoring stations and satellite observations, we analyzed the characteristics of air pollution from February 8 to 28, 2014 in Beijing. On the basis of $PM_{2.5}$ concentrations, we separated the whole data into three categories: relatively clean air ($PM_{2.5}$ concentrations less than 75 μg m^{-3}), haze ($PM_{2.5}$ concentrations greater than 75 μg m^{-3} but less than 200 μg m^{-3}) and heavy haze ($PM_{2.5}$ concentrations greater than 200 μg m^{-3}). The average concentrations of $PM_{2.5}$ are 29.5 μg m^{-3}, 136.6 μg m^{-3} and 311.2 μg m^{-3} for relatively clean air, haze and heavy haze cases, respectively. The NOAA HYSPLIT model and receptor models were used to analyze the potential source areas for the elevated $PM_{2.5}$, NO_2 and SO_2 concentrations in Beijing. The model results revealed that for the haze case, E (43.5%) and S (35.8%) are the predominant clusters and pollutants in Beijing mainly originated from the south regions such as Dezhou, Liaocheng and Heze in Shandong province. For the heavy haze case, south and east clusters accounted for 65.6% and 34.4%, respectively. The source areas of Baoding, Hengshui and Handan in Hebei province are responsible for the extremely high $PM_{2.5}$ concentrations in Beijing for the heavy haze case. Moreover, the analysis results of NO_2 and SO_2 indicated that the potential source areas in Jinzhou, Liaoning province, also has an important contribution to the higher NO_2 and SO_2 concentration in Beijing. The correlation analyses indicate that $PM_{2.5}$ formation is affected by the sources similar to those of CO such as combustion, industry, mobile, and oxidation of hydrocarbons. The conclusions indicate that the surrounding provinces emissions have crucial contribution for Beijing's air pollution. Thus,

it is necessary to implement air pollution control for all surrounding areas, especially for the industrial zones locating in south/southwest of Beijing. It is of interest to note that the citied responsible for the high $PM_{2.5}$ concentrations and haze formation in Beijing identified in our work are consistent with those cities imposing emergency restrictions with a special air pollution control plan to ensure clean air in Beijing during the APEC period. On the other hand, success of the "APEC blue" has spurred confidence that clean air is attainable and reducing emissions and air pollution in the region as a whole is key to ensuring blue skies and good air quality in Beijing.

Acknowledgments

The part of this work is supported by the "Zhejiang 1000 Talent Plan" and Research Center for Air Pollution and Health in Zhejiang University.

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