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Characteristics and origins of a typical heavy haze episode in Baotou, China: implications for the spatial distribution of industrial sources*

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Abstract: Air pollution has become the predominant environmental problem caused by rapid industrialization and urbanization in China. In this study, measurements of the concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 at six monitoring stations in Baotou, China were used to investigate the characteristics of heavy haze pollution in Dec. 12–25, 2013. Source locations of $PM_{2.5}$ in Baotou were identified using satellite remote sensing data, an air mass trajectory model, and a conditional probability function (CPF). The results showed that the average concentrations of $PM_{2.5}$ and PM_{10} were (113.8±84.0) μg/m^3 and (211.1±149.2) μg/m^3, respectively. The similar trends in temporal variation of the air pollutants $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO suggested they may share common sources. The results of satellite observations and backward trajectories supported the hypothesis that the pollutants causing the haze event originated mainly from local anthropogenic sources. According to the CPF analysis, low-speed winds from the south and southwest, upwind industrial emissions, and the northern mountains were mainly responsible for the formation of haze in Baotou. The study provides some insights to help governments optimize industrial layouts for improving air quality in the future.

Key words: Air pollution; Haze; Industrial sources; Backward trajectory; Conditional probability function (CPF)
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1 Introduction

Over the past three decades, China has experienced phenomenal economic and industrial development accompanied by expansion of the urban population (Mao *et al*., 2006; Yan *et al*., 2006). This rapid growth in such a short period has caused severe air pollution in megacities (Shao *et al*., 2006; Chan and Yao, 2008). The severity of air pollution can be affected by the composition of pollutants. Fine particulate matter ($PM_{2.5}$, particulate matter with an aerodynamic diameter of less than 2.5 μm) is largely responsible for haze formation (recorded as days with visibility <10 km under conditions of 80% relative humidity) (Chan and Yao, 2008; Zhang *et al*., 2011). Monitoring data from 74 major cities in China showed that most cities had suffered severe and persistent haze pollution in the first three months of 2013 (Huang *et al*., 2014). $PM_{2.5}$ contains various chemical components, including toxic or mutagenic matter, and

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can easily penetrate the human bronchi and lungs (Seinfeld, 1989; Pope *et al.*, 1995; Yu *et al.*, 2014b). Moreover, long-term exposure to high $PM_{2.5}$ concentrations can lead to increasing morbidity and mortality (Dockery and Pope, 1994; Pope *et al.*, 1995).

Hence, particle matter (PM) pollution has become the most concerning environmental problem and the identification of its sources is vital to clarify the mechanism of formation of heavy haze (Tan *et al.*, 2009; Zhang *et al.*, 2013; Wang H. *et al.*, 2015). Receptor models, such as factor analysis, tracer-based and meteorology-based methods, have been used to identify and quantify source contributions to air pollution based on measurements of species or meteorological conditions at receptor sites (Watson *et al.*, 2008). As well-adopted models, backward trajectory models and the conditional probability function (CPF) have been used in some studies that attempted to estimate the potential source location or examine the relationship between source contributions and wind directions (Kim and Hopke, 2004; Wang Y.Q. *et al.*, 2006; Wang F. *et al.*, 2010; Oh *et al.*, 2011; Cheng *et al.*, 2013; Karnae and John, 2013; Liu N. *et al.*, 2013). For example, using backward trajectory clustering and receptor models, Yu *et al.* (2014c) reported that air masses causing heavy haze in Hangzhou originated from local areas and nearby provinces, indicating the key role of regional transport of pollutants in air pollution. Xiao *et al.* (2012) used CPF to analyze the directional distribution of some elements in $PM_{2.5}$ collected from a roadside in the southwest of Beijing during May 2007 to November 2009, revealing that the elements might originate mainly from industrial activities.

High consumption of coal and a high intensity of industrial emissions could make a significant contribution to heavy haze formation in cities with heavy industries (Song *et al.*, 2007; Zhang *et al.*, 2013; Liu *et al.*, 2015). The health of residents in Baotou, one of the most important industrial cities in China, has been significantly affected by industrial emissions (Cheng *et al.*, 2000). The characteristics of pollution in Baotou are different from those of the "coal burning-vehicle composite pollution" in the developed coastal areas (e.g., in the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), and Pearl River Delta (PRD) regions) where numerous studies have been done (Lan, 2011). But most studies of source identification in Baotou focused only on estimating contributions from different sources (Ma, 2004; Gao *et al.*, 2014; Zhang and Zhang, 2014). To our knowledge, the relationship between industrial spatial distribution and haze formation in Baotou, China is still unknown. Considering that reasonable spatial distribution of industrial sources is helpful to reduce the occurrence of heavy haze in urban areas, in this paper, we discuss the results of an analysis of a heavy haze event observed in Baotou in Dec. 12–25, 2013, including: (1) the characteristics of air pollution and the impact of cross-border transport of pollutants based on the observed data, air mass backward trajectory analysis, and the results of satellite remote sensing data; (2) the influence of local industrial sources on the high $PM_{2.5}$ concentrations identified by CPF; (3) the effect of industrial spatial distribution on haze formation and future controlling strategies in Baotou.

2 Data and methods

2.1 Description of study area

Baotou is located in northwest China (40.65° N, 109.88° E) and has a population of 2766 000 and an area of 27768 km^2. The Daqing and Wula mountains are situated to the north of the urban areas with an average altitude of 2000 m above sea level (Fig. 1a). The climate in Baotou is characterized as temperate continental monsoon semi-arid. Dust events occur frequently in Baotou during spring due to dust transport from the western semi-arid regions such as the Taklimakan, Gobi, and Gurbantunggut deserts.

Urban Baotou has five districts (Kundulun, Qingshan, Shiguai, Jiuyuan, and Donghe (Fig. 1b)) with a combined area of 2590 km^2. The Qingshan and easthern Kundulun districts are the commercial and most populated areas. Numerous industrial sources are located in the Kundulun and Donghe districts, including the Baotou Steel Industrial Zone. Baotou is famous for its advanced industrial productivity in China. As a typical industrial city, in 2013, the coal consumption of industrial activities in the city reached 37.06 million tons, accounting for 80.78% of the total consumption of coal in Baotou. Consequently, high coal consumption for industrial production, power generation, and domestic burning coupled with the stable synoptic system leads easily to extreme PM pollution, especially in winter.

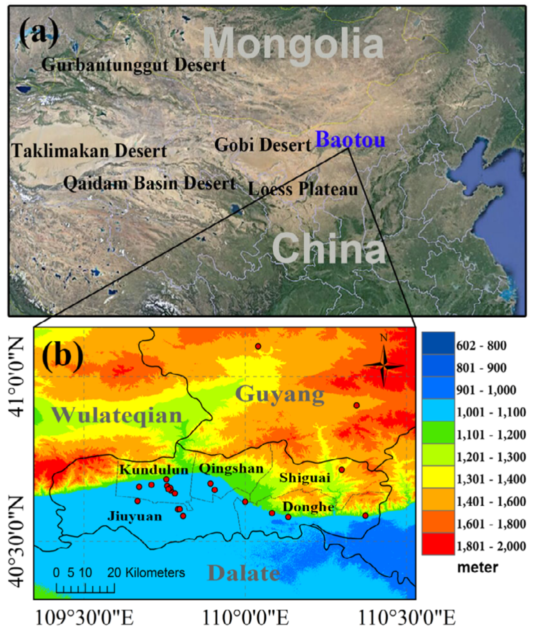

Fig. 1 Location (a) and topography (b) of Baotou
Urban areas consist of Kundulun, Qingshan, Shiguai, Jiuyuan, and Donghe districts; the surrounding counties are Wulateqian, Guyang, and Dalate. The red points represent the industrial sources (including the power industry) which were enlisted in the National Key Supervision Enterprises Project in 2013 (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

2.2 Ground observations, moderate resolution imaging spectroradiometer, and meteorological data

Hourly data of the concentration of air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) were obtained via the China National Environmental Monitoring Center (CNEMC) for six monitoring stations in Baotou: Shihuanjing monitoring station (40.65° N, 109.88° E), Baobai building (40.66° N, 109.81° E), Donghechenghuanju (40.59° N, 110.01° E), Qingshan hotel (40.6821° N, 109.85° E), Huilong logistics (40.63° N, 109.87° E), and Donghehonglongwan (40.55° N, 110.04° E). Data for SO_2 and NO_x emissions from industrial sources which belonged to the National Key Supervision Enterprises Project were obtained from the Baotou Environmental Protection Agency (http://www.baotou-epb.gov.cn/index.asp) and the Inner Mongolia Self-monitoring Information of Key Supervision Enterprises Publishing Platform (http://nmgepb.gov.cn:8088/enterprisemonitor/webpage!indexPage.action).

The deep-blue aerosol optical depth (AOD) at 550 nm obtained from Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) was used to evaluate the regional transport of pollutants in this study. The deep-blue algorithm can be used to calculate AOD over bright surfaces such as deserts where the standard MODIS AOD algorithm does not work well (Tao *et al.*, 2012). Because the deep-blue data of the aerosol were not available for Terra after December 2007 due to unavailability of the required polarization corrections to the L1B data, we selected MYD08_D3.051 data (Level-3 data) from Aqua with 1°×1° spatial resolution in Dec. 12–26, 2013.

The global surface meteorological dataset from the China Meteorological Data Sharing Service System is commonly used in studies. However, the level of detail in this dataset (3-h intervals) was inadequate for this 14-d case study using CPF, which is based on statistical methods. Therefore, the Weather Research and Forecasting Model (WRF) was used to improve the temporal resolution of the meteorological inputs. The initial conditions and boundary conditions for WRF were obtained from the National Centers for Environmental Prediction (NCEP) data every 6 h with a 1°×1° resolution. In this study, the WRF model was initialized with the Morrison two-moment cloud microphysics scheme, the Rapid Radiative Transfer Model (RRTM) short wave and long wave radiation scheme, the Pleim-Xiu (PX) land-surface scheme, the Asymmetric Convective Model (ACM2) planetary boundary layer (PBL) scheme, and the Kain-Fritsch (KF2) cumulus cloud parameterization based on Yu *et al.* (2014a). Comparisons of the WRF simulation outputs with meteorological measurements were conducted to demonstrate reasonable consistency.

2.3 Air mass back trajectory

The NOAA HYSPLIT (hybrid single-particle Lagrangian integrated trajectory) model was employed to trace air masses which arrived in Baotou during this haze episode to evaluate the contribution of regional sources to the haze formation in Baotou. Considering that the surface data used by CPF analysis were accessed from WRF modeling and the meteorological inputs should be consistent in this study, we obtained the meteorological data input to the trajectory model via conversion from WRF outputs to ARL format files (Liu N. *et al.*, 2013). 3D 48-h backwards trajectories of air masses arriving in Baotou were calculated eight times per day (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 local time) based on Yu *et al.* (2014c). Different arrival heights (100, 500, and 1000 m above ground level) of backward trajectories were conducted to identify whether the transport pathways were sensitive to the heights selected in this study.

2.4 Conditional probability function

Wind directions are often used in various receptor models to identify local sources (Watson *et al.*, 2008). Because wind directions can be considered as constant within a limited distance, they are more relevant to pollutant concentrations focusing on urban scales.

CPF estimates the probability that source contributions from a given wind direction sector will exceed a predetermined threshold criterion, as described by Ashbaugh *et al.* (1985). The source contributions detected by a given monitoring station and wind direction data matching each source contribution in time were used in the analysis. Following Cheng *et al.* (2013), the upper 25th percentile of the fractional contribution from the sources was set as the threshold criterion in this study. The wind direction was segregated at a 10° resolution for a total of 36 sectors, and calm wind conditions with wind speed less than 0.1 m/s were excluded, based on Watson *et al.* (2008). The calculation of CPF was determined by

$$\mathrm{CPF}(\theta)=\frac{m_{\Delta\theta}}{n_{\Delta\theta}}, \quad (1)$$

where $m_{\Delta\theta}$ is the number of occurrences in the direction sector $\theta\rightarrow\theta+\Delta\theta$ that exceeds the specified source contributions threshold, and $n_{\Delta\theta}$ represents the total number of wind occurrences in that sector.

3 Results and discussion

3.1 Characteristics of air pollutants

Baotou frequently experienced extreme haze in December 2013. Fig. 2 shows the temporal variation in hourly average concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 at six monitoring sites in Baotou in Dec. 12–25, 2013.

The daily concentrations of $PM_{2.5}$ showed two periods of marked increase (Dec. 13–16 and 18–25) during this pollution period, and the hourly concentrations exceeded 300 μg/m^3 at midnight on Dec. 24. Concentrations of other pollutants, except O_3, showed similar trends, which revealed that emissions from human-activities were the main sources of $PM_{2.5}$. The mean hourly concentrations of $PM_{2.5}$ and PM_{10} during this haze episode were (113.8±84.0) μg/m^3 and (211.1±149.2) μg/m^3, respectively. These values were much higher than those of a normal period (Oct. 10–25) with average $PM_{2.5}$ and PM_{10} concentrations of (63.8±78.8) μg/m^3 and (150.8±123.4) μg/m^3, respectively. The daily average concentrations of $PM_{2.5}$ and PM_{10} exceeded the national ambient air quality standards (75 μg/m^3 for $PM_{2.5}$ and 150 μg/m^3 for PM_{10}) for 12 d (Dec. 13–16 and 18–25) and 11 d (Dec. 14–16 and 18–25), respectively. The maximum daily concentration of $PM_{2.5}$ was observed on Dec. 24, with a value which was nearly three times the daily limit of the national standard. The average concentrations of SO_2, NO_2, and CO during the haze period were (134.2±100.2) μg/m^3, (61.0±26.4) μg/m^3, and (3.50±2.35) mg/m^3, respectively. For most of the time, hourly SO_2, NO_2, and CO concentrations were lower than the corresponding national standards (500 μg/m^3 for SO_2, 200 μg/m^3 for NO_2, and 10 mg/m^3 for CO). The O_3 concentrations showed a remarkable diurnal variability. The highest value of 60.2 μg/m^3 was much lower than the hourly national standard of 200 μg/m^3.

CO is frequently used to normalize PM concentrations to certify the impact of primary pollution since it is a long-lived pollutant and can be emitted directly from emission sources such as coal burning, vehicles, and the oxidation of hydrocarbons (Zhang and Cao, 2015). In this study, there were the strong correlations between the concentrations of $PM_{2.5}$ and the pollutants NO_2, SO_2, and CO, especially CO (data not shown). This suggests that the $PM_{2.5}$ originated from primary as well as secondary particles. The $PM_{2.5}/PM_{10}$ ratio was 0.54 in this study, which was lower than those of the coastal cities in the haze period. In some coastal megacities, the $PM_{2.5}/PM_{10}$ ratio can commonly reach 0.7 during an air pollution period (Wang X.H. *et al.*, 2006; Wang J. *et al.*, 2013; Shen *et al.*, 2014). The $PM_{2.5}/PM_{10}$ ratio reached 0.78 in Hangzhou during a heavy haze episode from Nov.

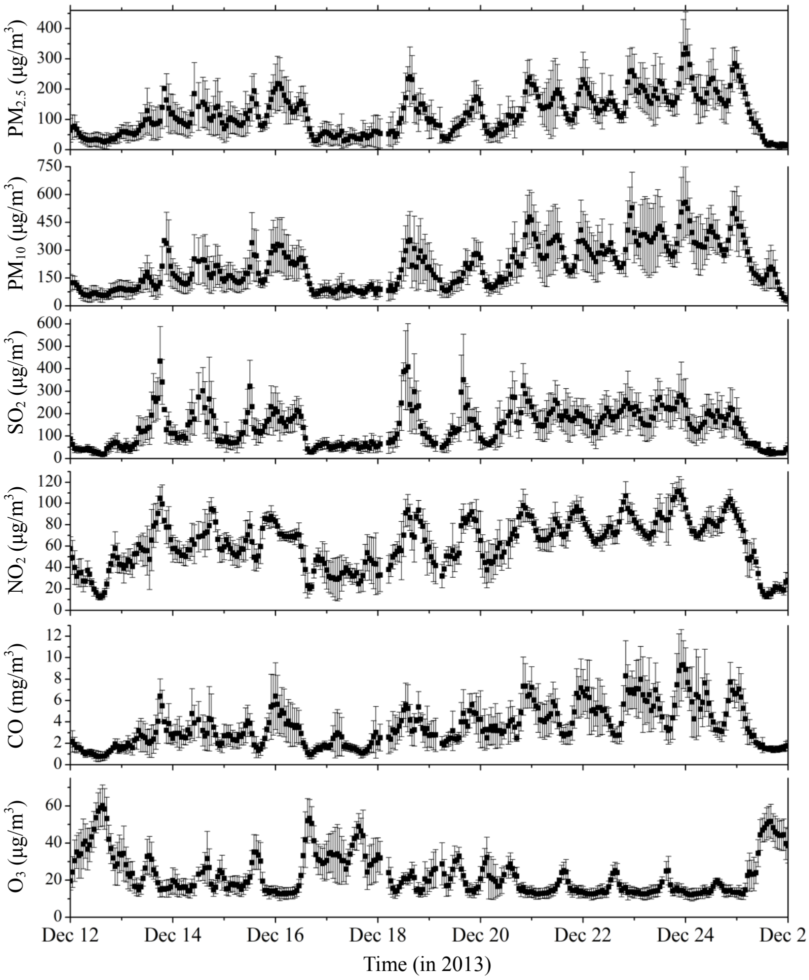

Fig. 2 Temporal variation in hourly average concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 at six sites in Baotou in Dec. 12–25, 2013

25 to Dec. 11, 2013 (Yu *et al.*, 2014c). Yan *et al.* (2015) reported that the $PM_{2.5}/PM_{10}$ ratio for severe haze pollution in Beijing was 0.88 in February 2014, concluding that dust-producing activities were not the main sources of PM_{10} pollution. Coarse particles (aerodynamic diameter in the range 2.5–10 μm) accounted for 46% of PM_{10} suggesting that dust-producing activities were the main sources of PM_{10} pollution in Baotou. Dust from the western regions can accumulate easily on roads due to the semi-arid climate, and numerous stockpiles and heavy construction in the industrial zone can also increase dust production in Baotou.

3.2 Influence of regional pollutant transport

Due to the lack of large-scale surface monitoring stations, satellite remote sensing has often been used to determine the impact of dust storms or long-range transport of pollutants on urban air quality (Engelcox *et al.*, 2004). In this study, the MODIS-derived AOD data and the air mass backward trajectories were used to evaluate the impact of regional transport of pollutants and dust storms on haze formation in Baotou.

Fig. 3 presents the spatial distributions of AOD at 550 nm from the MODIS over eastern and northern China during Dec. 12–26, 2013. The variation of AOD values in Baotou was consistent with the temporal variation of hourly $PM_{2.5}$ concentrations. The AOD values were below 0.18 in Baotou in Dec. 12–18 with a slight increase on Dec. 15, then increased sharply and exceeded 0.9 on Dec. 24. The south (including the PRD region) and the east (including the YRD region) regions of China had suffered heavy haze before Dec. 18, and the plain of north China (including the Beijing-Tianjin-Heibei region) had haze conditions before Dec. 21 (Fig. 3). However, these areas suffered the haze pollution a few days earlier than Baotou. Then the heavy haze appeared gradually in Baotou in Dec. 21–24 (Fig. 3), which is easily misjudged that transport of pollutants from the south or southeast regions to Baotou resulted in the extremely high concentration of $PM_{2.5}$ in Baotou on Dec. 24.

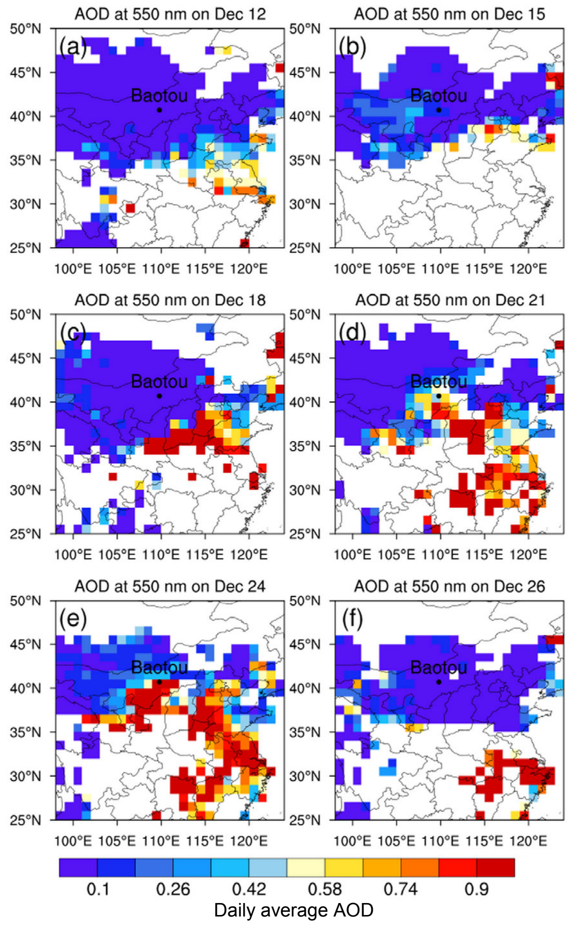

Fig. 3 Satellite observations of daily average AOD at 550 nm from MODIS over China on Dec. 12 (a), Dec. 15 (b), Dec. 18 (c), Dec. 21 (d), Dec. 24 (e), and Dec. 26 (f)

However, the 48-h backward trajectories during the whole period showed that most of the air masses arriving in Baotou originated from the west, northwest, north, and northeast regions in the atmospheric surface layer (100 m above ground) and upper air (500 and 1000 m above ground) (Fig. 4). None of the air masses originated from the heavy haze regions such as south and southeast regions (Fig. 3). Thus, long-range transport of pollutants via wind flow from polluted areas to Baotou might not have occurred. In addition, there was no obvious haze cloud or dust storm in the upwind regions throughout the period. These results do not support the influence of cross-border transport of pollutants on conditions in Baotou, and indirectly revealed that the sharp increase in $PM_{2.5}$ concentrations and AOD values in Baotou on Dec. 24 was due mainly to high emissions from local anthropogenic sources.

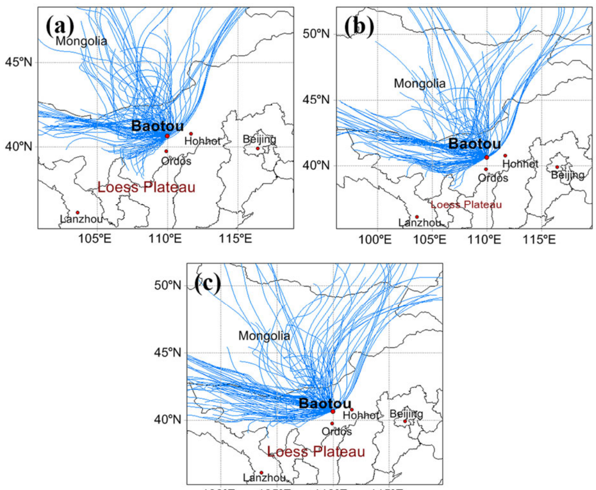

Fig. 4 48-h backward trajectories of air flows in Baotou at different altitudes: (a) 100 m, (b) 500 m, and (c) 1000 m

3.3 Local source contributions to $PM_{2.5}$ based on CPF

Wind direction, wind speed, and observed $PM_{2.5}$ data were analyzed to identify potential local sources by calculating CPF values (CPFs) for six monitoring sites over the entire study (Fig. 5). Considering that the industrial activities could significantly contribute to haze formation under unfavorable meteorological conditions in Baotou, the locations and emissions of industrial sources covered by the National Key Supervision Enterprises Project (Fig. 6) were used to examine the CPF results.

The CPFs were similar for the Shihuanjing monitoring station, Baobai building, Qingshan hotel, and Huilong logistics sites, probably due to their close proximity to each other compared with the other two monitoring sites (Donghechenghuanju and Donghehonglongwan) (Fig. 5). The CPFs of the four monitoring sites were high when winds were from the south, southwest, and west. These high CPFs could be attributed to the high intensity of industrial emissions in the upwind regions (Kundulun and Jiuyuan districts) (Fig. 6).

Seven of these industrial sources belonged to the Baogang Group, located in the Baogang Industrial Zone (in the east of Kundulun district) 3–8.5 km away from the four monitoring sites. The Baogang Group is one of the largest iron and steel production bases, with coal consumption of more than 10 million tons, emitting about 40 902 t of SO_2 and 34 439 t of NO_x in 2013. There were three additional sources located on the northern edge of Jiuyuan district, i.e., two heavy metal factories (copper, RE-Al) and a power plant, which were also in very close proximity to the four

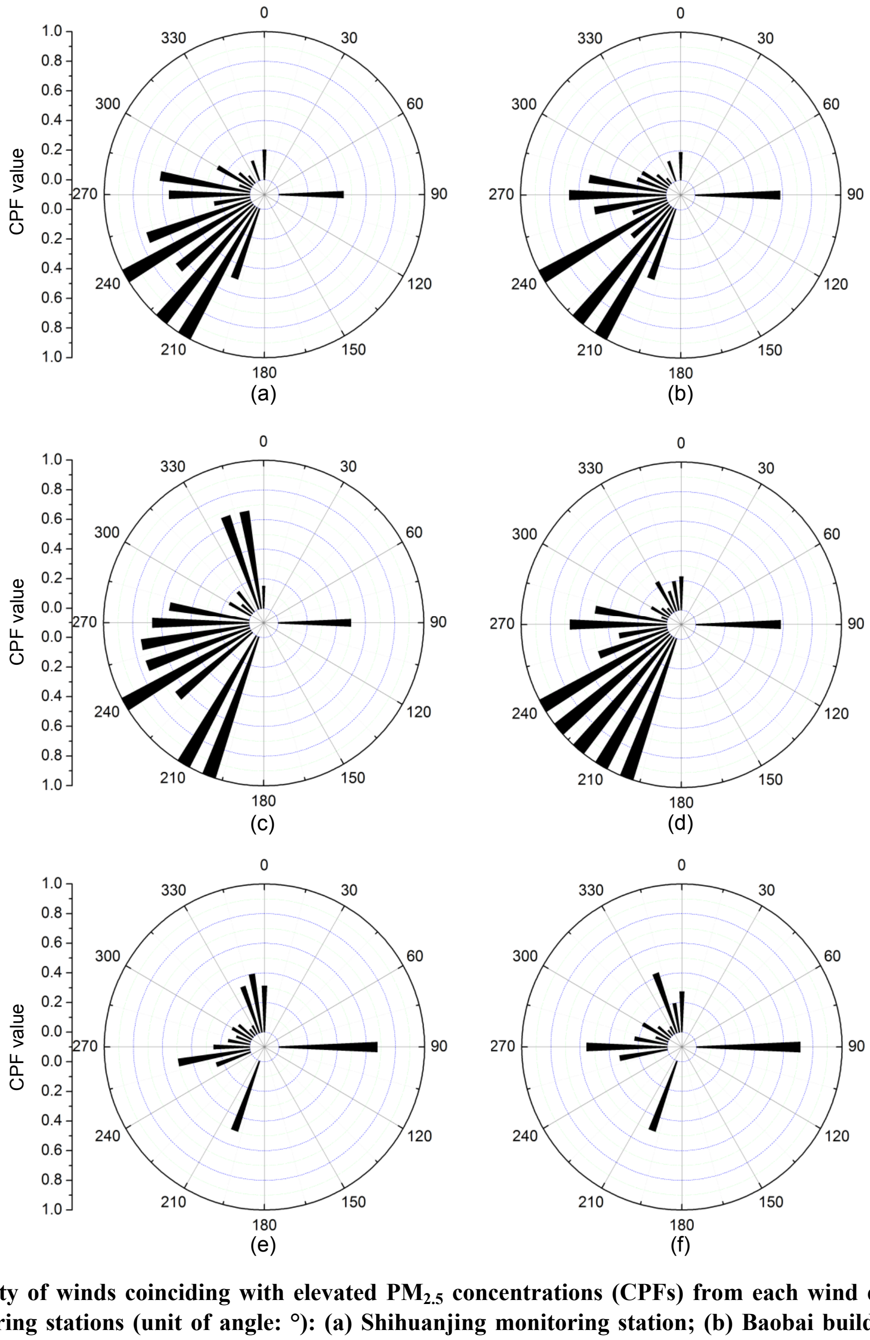

Fig. 5 Probability of winds coinciding with elevated $PM_{2.5}$ concentrations (CPFs) from each wind direction sector at different monitoring stations (unit of angle: °): (a) Shihuanjing monitoring station; (b) Baobai building; (c) Qingshan hotel; (d) Huilong logistics; (e) Donghechenghuanju; (f) Donghehonglongwan

monitoring sites (7.8–10 km). The high CPFs of the four monitoring sites in the south, southwest, and west wind sectors could be attributed to the emissions of industrial sources which were located in the vicinity of the monitoring stations (Figs. 5a–5d). Although many industrial sources were located in the west of the city, the CPFs in the west sectors were still lower than those in the south and southwest sectors. This could be explained by the effects of wind speed and the mountains to the north of the city. During the study period, the average speed of west winds was 2.70 m/s, which was about three times that of those from the south (0.84 m/s) and southwest (0.94 m/s). West winds with higher wind-speeds were more favorable for the diffusion of pollutants than the south and southwest winds. In addition, the mountains to the north of the city may have caused the pollutants to stagnate in urban areas when south and southwest winds flowed through the city. In contrast, the pollutants could diffuse to the east when winds came from west, due to the flat terrain of the eastern areas.

However, the characteristics of CPFs at the Donghechenghuanju and Donghehonglongwan sites were drastically different from those of the previous four sites, with higher CPFs observed in the eastern sectors. There was a power plant and an aluminum manufacturer located in the east, only 8.5–9 km away from the two monitoring sites, and their SO_2 emissions were nearly 17 827 t in 2013 (Fig. 6). The high intensity emissions from these two sources could have contributed to the high CPFs found in the eastern sectors of Donghechenghuanju and Donghehonglongwan.

Adverse weather conditions were another cause of haze formation in addition to emissions from industrial sources. Fig. 7a shows that the prevailing winds over the entire study period were from the north and northwest with an average wind speed of 2.93 m/s (max.>8 m/s). North and northwest winds could not only bring clear air from the Mongolian plateau and Zapadno Sibirskaya Ravnina but also favor the diffusion of pollutants by high wind speeds. As a result of high speed winds from the north and northwest, $PM_{2.5}$ concentrations in Baotou decreased after Dec. 16. However, the wind speed decreased rapidly to an average of 0.93 m/s when the wind direction changed to the south and southwest during the daytime on Dec. 21. The low-speed winds were not conducive to horizontal diffusion of pollutants, leading to continuous transport of pollutants from up-wind industrial sources to urban areas. In addition, the mountains located to the north of the urban districts were unfavorable for the transport of pollutants to the north, resulting in the stagnation of pollutants in urban areas when south and southwest winds dominated. Meanwhile, the low-speed winds and low temperature restricted the development of the planetary boundary layer (PBL) (Liu X.G. *et al.*, 2013) (Figs. 7a–7c). The pollutants in the PBL were "compressed" to a shallow layer with a decrease in the height of the PBL (about 700 m in the daytime in Dec. 21–24), resulting in a significant increase in ground contamination after Dec. 21.

The low speed of the south and southwest winds was responsible for the high CPFs in the southwest sectors while the high speed of the north and northwest winds resulted in the relatively low CPFs in the northwest sectors. However, some CPFs reached 1.0 (i.e., the probability of winds coinciding with elevated $PM_{2.5}$ concentrations reached 100 %) in the southwest direction. These values were probably anomalous, resulting from the relatively limited data available for analysis in the limited time span of the study. CPFs of 0.0 in the southeast and northeast sectors could be explained by the rare occurrence of southeast winds, which was explicitly shown by the backward trajectories (Fig. 4). Despite the limited amount of statistical data, the strong coincidence between the CPFs of different monitoring sites and the spatial distribution of industrial sources indicated that the high intensity of industrial activity could result in alarming levels of PM pollution in Baotou under haze-conducive meteorological conditions.

3.4 Strategic implications for haze in Baotou

In addition to emission levels, meteorological conditions could be a crucial factor determining the formation and levels of fine aerosols (Zhang *et al.*, 2013), and forecasted decreasing wind speed also favors air quality degradation (Chen *et al.*, 2012). In this study, the low speed of south or southwest winds and the mountainous terrain north of the city were unfavorable for the diffusion of pollutants, resulting in the accumulation of primary and precursor pollutants in the urban district and causing the heavy haze lasting even more than one week. Generally, the

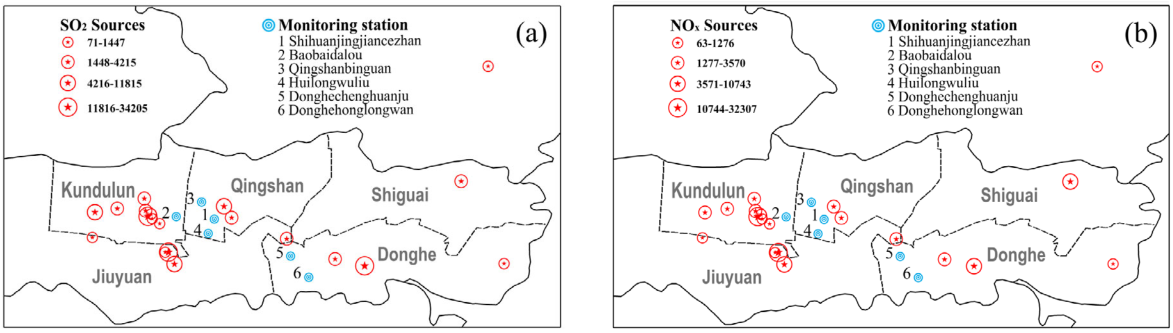

Fig. 6 Emissions from the main industrial sources in urban areas of Baotou in 2013 for SO_2 (a) and NO_x (b)
Red points are industrial sources, blue points represent monitoring stations, and the units of SO_2 and NO_x emissions are tons per year (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

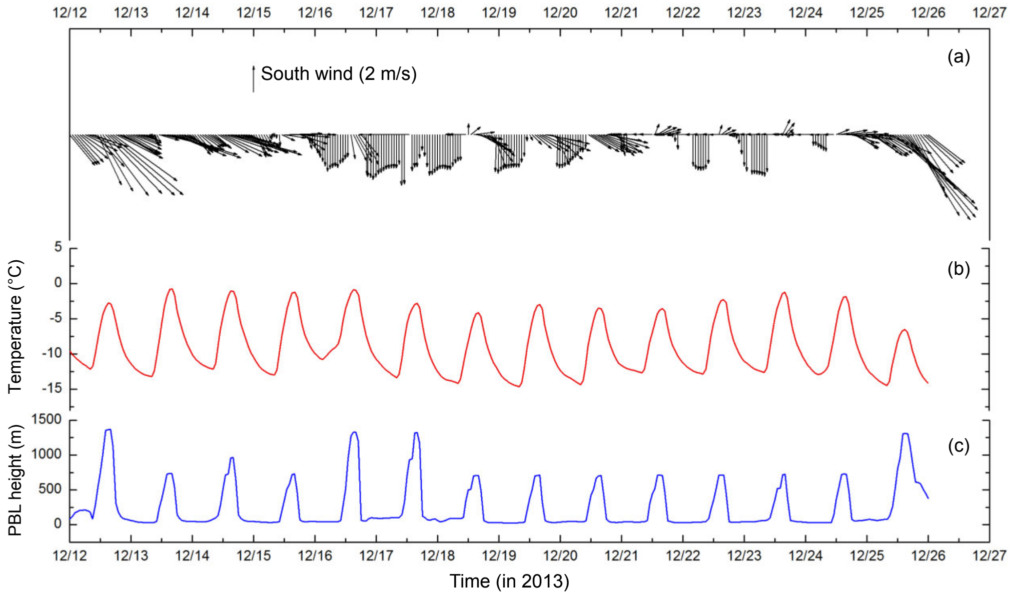

Fig. 7 Time series of meteorological parameters in Baotou in Dec. 12–25, 2013
(a) Wind direction and wind speed; (b) Temperature; (c) PBL height

prevailing winds from the northwest carried clean air masses and the scarcity of industrial sources located in the north of the city were thought to reduce occurrences of air pollution. However, the concentrations of pollutants could still increase rapidly once the winds came from south and southwest (Figs. 2 and 7a). This suggests that the non-prevailing winds, such as low-speed south and southwest winds, should not be ignored though they occur only infrequently during winter.

According to our analysis, the typical haze occurrence was mainly attributable to local industrial emissions. Therefore, to improve air quality in Baotou, special control measures should be highlighted to reduce industrial emissions. Since coarse particles can make a significant contribution to the PM_{10} pollution in Baotou, relevant control measures for dust-producing activities in the industrial zone should be implemented. Unfavorable meteorological factors were another main cause of the haze episode in Baotou. The results indicated that low-speed south or southwest winds facilitated haze occurrence. Therefore, the intensity of industrial activity should be reduced when such winds occur, especially for industrial sources located in the south, southwest, and west areas. The results of this study provide valuable information for the government to optimize industrial layouts in the future.

4 Conclusions

In recent years, air pollution has become the most concerning environmental problem in China. In this study, the characteristics of a severe haze episode in Dec. 12–25, 2013 in Baotou were analyzed based on surface measurements of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 concentrations at six monitoring stations. The average concentrations of $PM_{2.5}$ and PM_{10} during this haze episode were (113.8±84.0) μg/m^3 and (211.1±149.2) μg/m^3, respectively. The temporal variation of $PM_{2.5}$ concentration showed very similar trends as other pollutants (SO_2, NO_2, and CO), suggesting a significant contribution of anthropogenic emissions to haze formation. The strong correlations between $PM_{2.5}$ and other pollutants (NO_2, SO_2, and CO) and the $PM_{2.5}$/PM_{10} ratio value of 0.54 revealed the significant contribution of primary as well as secondary particles during the haze period. Furthermore, the analysis of MODIS-derived AOD combined with air mass trajectories suggested that cross-border transport of pollutants did not influence the heavy haze event in Baotou. This finding indirectly supports the view that the sharply elevated concentrations of pollutants were due mainly to emissions from local anthropogenic sources.

According to the CPF analysis, the elevated $PM_{2.5}$ concentrations in urban areas could be explained by the south and southwest winds and high emissions in the upwind regions, because these low-speed winds and the north mountains were unfavorable for the diffusion of pollutants. The present study indicated that besides the prevailing winds, the influence of non-prevailing winds with low speed should also be taken into consideration in the future when governments attempt to optimize the industrial layout in urban areas with a high intensity of industrial emissions.

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中文概要

题　目： 包头市重灰霾特征分析及对重工业布局的启示

目　的： 工业排放是大气中 $PM_{2.5}$ 的重要来源，是灰霾形成的主要贡献者之一。通过分析包头市一次典型灰霾时段的污染来源及特征，研究本地工业布局在此次灰霾时段对灰霾形成的影响，并讨论城市工业布局的合理性。

创新点： 针对我国典型重工业城市包头市进行案例分析，研究本地城区灰霾形成的原因及重工业布局对灰霾形成的影响，并为合理布局工业提供了新的启示。

方　法： 1. 结合污染物观测数据、卫星遥感数据及后向轨迹模式的结果，揭示此次重灰霾发生时段的污染特征，找出此次重灰霾的主要来源。2. 采用风向条件概率函数研究城区高浓度 $PM_{2.5}$ 与本地重工业布局间的关系。

结　论： 1. 在此次重灰霾时段，$PM_{2.5}$ 浓度的变化趋势与其他污染物相似，说明污染主要来自人为源，且在同样发生重灰霾的情况下，$PM_{2.5}$ 占 PM_{10} 的比例较其他沿海城市低，说明粗颗粒物对包头 PM_{10} 污染的贡献较其他城市大。2. 结合卫星遥感数据与后向轨迹模式的结果，可以排除外来污染物的输入，并断定形成此次重灰霾的主要原因为本地人为源。3. 风向条件概率函数分析结果显示本地重工业分布以及低风速的西南风（非盛行风）是造成此次重灰霾发生的主要原因。4. 揭示了包头市在布局重工业或进行高强度的工业活动时不能只考虑避开盛行风，因为出现次数不多的低风速非盛行风同样会引起重灰霾的爆发；这可为包头市乃至其他工业城市在进一步调整工业布局时提供参考。

关键词： 空气污染；灰霾；工业布局；后向轨迹；风向条件概率函数