Influences of Meteorological Conditions on Interannual Variations of Particulate Matter Pollution during Winter in the Beijing–Tianjin–Hebei Area

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ABSTRACT

To investigate the interannual variations of particulate matter (PM) pollution in winter, this paper examines the pollution characteristics of PM with aerodynamic diameters of less than 2.5 and 10 μm (i.e., $PM_{2.5}$ and PM_{10}), and their relationship to meteorological conditions over the Beijing municipality, Tianjin municipality, and Hebei Province—an area called Jing–Jin–Ji (JJJ, hereinafter)—in December 2013–16. The meteorological conditions during this period are also analyzed. The regional average concentrations of $PM_{2.5}$ (PM_{10}) over the JJJ area during this period were 148.6 (236.4), 100.1 (166.4), 140.5 (204.5), and 141.7 (203.1) μg m^{-3}, respectively. The high occurrence frequencies of cold air outbreaks, a strong Siberian high, high wind speeds and boundary layer height, and low temperature and relative humidity, were direct meteorological causes of the low PM concentration in December 2014. A combined analysis of PM pollution and meteorological conditions implied that control measures have resulted in an effective improvement in air quality. Using the same emissions inventory in December 2013–16, a modeling analysis showed emissions of $PM_{2.5}$ to decrease by 12.7%, 8.6%, and 8.3% in December 2014, 2015, and 2016, respectively, each compared with the previous year, over the JJJ area.

Key words: particulate matter pollution, local meteorological conditions, circulation types, Siberian high

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1. Introduction

With rapid economic development and an increasing number of vehicles, severe air pollution occurs frequently in China (He et al., 2017a) and threatens human health (An et al., 2015; Song et al., 2017). The area encompassing the Beijing municipality, Tianjin municipality, and Hebei Province—referred to by local Chinese people as the Jing–Jin–Ji (JJJ) area—is one of the most severely polluted regions in China (Hu et al., 2014). Statistics reveal that, as of 2016, 6 out of 10 of the most polluted cities were located in the JJJ area (https://www.zq12369.com/index.php). The concentrations of primary pollutants during winter are significantly higher than in other seasons (Zhao et al., 2016), and the largest major pollutant in the JJJ area is particulate matter (PM; He et al., 2017a). The severe air pollution in the JJJ area has attracted wide attention by the government, the public, and many researchers.

Pollutant emissions and meteorological conditions are

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two key factors in controlling urban air quality (Gao et al., 2011; Wang et al., 2015; He et al., 2016a; Liu et al., 2017). Pollutant emissions that exceed atmospheric environmental capacity are the primary cause of atmospheric pollution (An et al., 2007). The total emissions of sulfur dioxide in the JJJ area reached 1.59 × 10^6, 1.48 × 10^6, and 1.37 × 10^6 tons in 2013, 2014, and 2015, respectively, and 2.13 × 10^6, 1.95 × 10^6, and 1.74 × 10^6 tons for nitrogen oxides (National Bureau of Statistics and Ministry of Environmental Protection, 2015). Although total emissions have decreased year by year in the JJJ area, an unusual increase in air pollutant concentrations during the most recent winter was detected, which might have been related to adverse meteorological conditions (Chang et al., 2016; Liu et al., 2017). Previous studies have revealed that meteorological conditions are the main factor driving day-to-day variations of pollutant concentrations (Pearce et al., 2011; Lee et al., 2012; He et al., 2016a, 2017a). Air pollutant diffusion, transfer, and transport are significantly affected by boundary layer meteorology (Chen et al., 2009, 2016; Zhang et al., 2011). The air quality in northern China has a prominent correlation with pressure systems (Chen et al., 2008). However, to a certain extent, local meteorology plays a more import role in air pollution than large-scale circulation types (He et al., 2016a). The influence of meteorological conditions on air pollution is different for different timescales (He et al., 2016b). Both emissions and meteorological variations dominate the long-term pollutant concentration trend (Wang et al., 2015). The long-term trend of air pollution as correlated with meteorological conditions and emissions has been investigated in previous studies (Niu et al., 2010; Chen and Wang, 2015). A new “ambient air quality standard” was published by the Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine of China in 2012. However, studies on the impact of meteorological conditions with a focus on recent years over the JJJ area have been relatively few.

Although central and local governments throughout China have made great efforts to control air pollution, it remains a serious problem during winter in the JJJ area; the PM concentration in December 2015 even increased over the JJJ area compared to December 2014 (Liu et al., 2017). Understanding the role played by meteorological conditions and emissions control measures in recent years is very important for the development of further controls in the future. Accordingly, this paper reports an investigation into the pollution levels of PM with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) and less than 10 μm (PM_{10}), as well as the meteorological conditions and their influence, in December 2013–16 in the JJJ area. A modeling study was also conducted to investigate the change in emissions. In Section 2, the data and methods are described; the PM pollution characteristics and the influence of meteorological conditions are discussed in Section 3; and finally, the study’s conclusions are presented in Section 4.

2. Data and methods

2.1 *Meteorological data*

To investigate the relationship between air pollution and meteorological conditions, site observation data of 2-m temperature (T2), 2-m relative humidity (RH2), and 10-m wind speed (WS10) were acquired in December 2013–16 from the Meteorological Information Comprehensive Analysis and Process System of the China Meteorological Administration (CMA). We also examined ERA-Interim data, including sea level pressure (SLP) and boundary layer height (BLH), collected in December 2013–16. ERA-Interim data can be downloaded at a spatial resolution of 0.25° × 0.25° and temporal resolution of 6 h from http://apps.ecmwf.int/datasets/. The gridded data of BLH were interpolated to site level to analyze the relationship with $PM_{2.5}$ and PM_{10} concentrations.

Previous studies have documented a close association between pollution and the East Asian winter monsoon (Hien et al., 2011). The Siberian high index is an important index to use when describing the winter monsoon. The Siberian high intensity (SHI), which is defined as the average SLP covering within 40°–65°N, 80°–120°E, is widely used to describe the variability of the Siberian high (Jeong et al., 2011). The SHI is negatively correlated with wintertime aerosol optical depth (AOD) over North China (Jia et al., 2015). A new indicator, the Siberian high position index (SHPI), recently constructed by Jia et al. (2015), shows a significant negative correlation of 0.76 ($p < 0.01$) with MODIS (Moderate-resolution Imaging Spectroradiometer) AOD in North China. The units of the SHPI are measured in degrees of longitude. The SHI and SHPI indices in December 2013–16 were used in the present study to investigate the interannual variations of $PM_{2.5}$ and PM_{10} concentrations over the JJJ area.

2.2 *Air quality data*

In January 2013, the real-time hourly average concentrations of six pollutants based on data from air quality monitoring stations in major Chinese cities were released to the public and can be accessed via https://www.zq12369.com/index.php. During this study, hourly average $PM_{2.5}$ and PM_{10} concentrations in 13 cities in the JJJ area were collected in December 2013–16: Beijing (BJ), Tianjin (TJ), Shijiazhuang (SJZ), Handan (HD), Xingtai (XT), Hengshui (HS), Cangzhou (CZ), Baoding (BD), Langfang (LF), Tangshan (TS), Qinhuangdao (QHD), Chengde (CD), and Zhangjiakou (ZJK). The locations of these 13 cities are shown in Fig. 1. Although the quality assurance of hourly average concentrations was conducted before the data were released to the public, further quality control is necessary. The method of quality control used in this study is consistent with that employed in our previous research (He et al., 2017a).

2.3 *Circulation type*

Air pollution is closely related to circulation types in the JJJ area (Zhang et al., 2012; He et al., 2016c; Wu et al., 2017). The gridded SLP data covering within 35°–45°N, 110°–125°E were used to identify circulation types. The SLP at 0800 BT (Beijing Time) was selected to identify circulation types because it assimilated a significant amount of observed data and could better describe the pressure distribution than at any other time. Five techniques—namely, the correlation method, cluster analysis, principal component analysis (PCA), fuzzy method, and nonlinear method—are frequently used for circulation classification (Zhang et al., 2012). Here, a combination of the *T*-mode PCA and *K*-means clustering methods was used, since previous studies have demonstrated that this is the best approach for revealing data structures and identifying circulation types effectively (Huth, 1996). Data processing included four steps: First, we reshaped the SLP from a three-dimensional array (longitude × latitude × time) to a two-dimensional array (grid number × time). Second, the reshaped SLP data were normalized with the *z*-score method. Third, the main components were acquired from the normalized SLP with the PCA method according to the cumulative variance contribution of 85%. Fourth, circulation types were identified with the *K*-means clustering method. The number of circulation types was determined by the criterion function (Liu and Gao, 2011).

2.4 *Correlation analysis*

Pearson's product-moment correlation coefficient describes the linear correlation between two normally distributed variables, and is more effective compared to other correlation coefficients. Spearman's rank correlation coefficient was used for correlation analysis of variables that did not satisfy the normal distribution. With a significance level of 0.05, the Kolmogorov–Smirnov test was used to check whether the meteorological parameters and pollutant concentrations followed the normal distribution. Finally, the *t*-test was used to test the significance of correlation coefficients.

3. Results and discussion

3.1 *PM pollution characteristics*

Figure 1 shows the spatial distribution of the average $PM_{2.5}$ and PM_{10} concentrations in the JJJ area in December 2013–16. The concentrations of $PM_{2.5}$ and PM_{10} decrease from the south to the north of the study region. The average concentration of $PM_{2.5}$ (PM_{10}) ranges from 36.7 (86.2) to 194.9 (299.9) μg m^{-3}. The highest concentration of $PM_{2.5}$ (PM_{10}) appears in BD (HD), and the lowest in ZJK. As reported in previous studies (e.g., He et al., 2017b), several PM emission sources are located in southeastern JJJ, which explains the high concentrations of $PM_{2.5}$ and PM_{10} in this area. A spatial difference in meteorology is another factor affecting the PM concentration distribution. Because of the winter monsoon, the wind speed in northern JJJ is often greater than in southern JJJ. In addition, a large amount of wind often occurs along the coast because of the land–sea distribution. A large amount of wind is beneficial for pollutant dispersion and results in relatively low concentrations of $PM_{2.5}$ and PM_{10} in northern and eastern JJJ.

Figure 2 shows the daily mean PM concentrations in

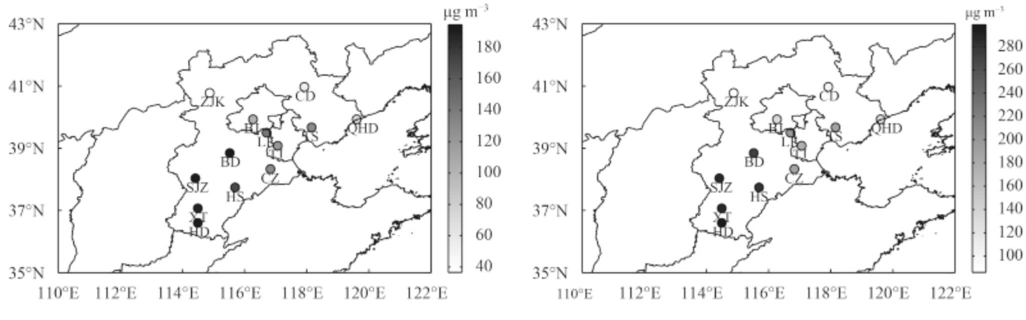

Fig. 1. Mean (a) $PM_{2.5}$ and (b) PM_{10} concentration distributions in December 2013–16.

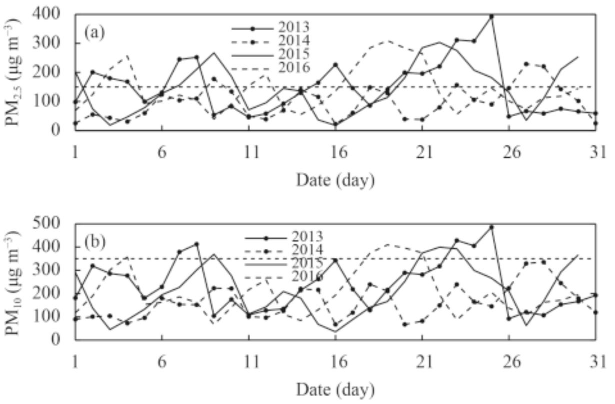

Fig. 2. Daily mean (a) PM$_{2.5}$ and (b) PM$_{10}$ concentrations in December 2013–16 over the JJJ area. The gray dotted lines represent the critical value for serious air pollution.

December 2013–16. The days featuring serious pollution, based on the daily mean PM$_{2.5}$ concentration (larger than 150 μg m^{-3}), reach 13 days in December 2013–15, and 9 days in December 2016. Only 4 days are seriously polluted in December 2014. A serious pollution period reaching 6 days is found in December 2013, with maximum daily mean PM$_{2.5}$ and PM$_{10}$ concentrations of 391.9 and 485.4 μg m^{-3}, respectively, over the JJJ area.

In recent years, central and local governments have made notable efforts to control air pollution. The interannual variation of pollutant concentrations is a pressing issue for the government and the public. Table 1 exhibits the monthly mean concentrations of PM$_{2.5}$ and PM$_{10}$ in December 2013–16 over the JJJ area. Compared to December 2013, a significant decrease in PM concentration was detected in December 2014, with a decrease of 33% and 51% for PM$_{2.5}$ and PM$_{10}$, respectively. However, increasing PM concentrations appeared in December 2015, and the concentrations of PM$_{2.5}$ and PM$_{10}$ in December 2016 were largely the same as those in December 2015. Overall, total emissions decreased year by year in the JJJ area (National Bureau of Statistics and Ministry of Environmental Protection, 2015). Therefore, the unusual increase in PM concentration was most likely related to unusual meteorological conditions.

3.2 *Impact of meteorological conditions*

Based on the Kolmogorov–Smirnov test, daily average PM concentrations and some meteorological parameters do not satisfy the normal distribution in the JJJ area. Therefore, Spearman's rank correlation coefficient was used for correlation analysis. Before analyzing the relationship between meteorological parameters and PM concentrations, the correlation coefficients between daily mean meteorological parameters are discussed (Table 2). Winter temperature was significantly correlated with winter monsoon, with a correlation coefficient of –0.52. RH2 was significantly correlated with other meteorological parameters (except temperature). It should be noted that the enhancement of atmospheric diffusion conditions (large WS10 and BLH) reduced RH2 in winter over the JJJ area. The correlation coefficient between WS10 and BLH was 0.79, which implies that the development of the atmospheric boundary layer (or turbulence) is mainly caused by dynamic rather than thermodynamic mechanisms in winter over the JJJ area. BLH was also significantly correlated with the SHI, with a correlation coefficient of 0.48. Attaining deep insight into the relationships between meteorological parameters can help us in understanding the relationship between PM concentrations and meteorological parameters, as shown in the following analysis.

WS10 and BLH reflect the turbulent mixing and dispersion capability of the atmosphere. High wind speeds and a high BLH are beneficial to the horizontal and vertical dispersion of pollutants. PM$_{2.5}$ and PM$_{10}$ concentrations were negatively correlated with WS10 and BLH (Fig. 3), and were positively correlated with T2 and RH2. Hygroscopic condensation growth of aerosol results in a positive correlation between PM concentrations and RH2. On the other hand, significant negative correlations between RH2 and WS10 and BLH (Table 2) may have resulted in the positive correlation between PM concentrations and RH2. A strong winter monsoon contributes to the rapid dispersion of pollutants in the JJJ area. The SHI (SHPI) was negatively (positively) correlated with PM concentration in the JJJ area. These findings regarding the correlation between PM concentrations and meteorological parameters are consistent with

Table 1. Monthly mean PM concentrations (μg m^{-3}) and ratios of monthly mean concentrations between PM$_{2.5}$ and PM$_{10}$ in December over the JJJ area

	2013	2014	2015	2016
PM$_{2.5}$	148.6	100.1	140.5	141.7
PM$_{10}$	236.4	166.4	204.5	203.1
PM$_{2.5}$/PM$_{10}$	0.63	0.60	0.69	0.70

Table 2. Correlation coefficients between daily mean meteorological parameters in December 2013–16

	T2	RH2	WS10	BLH	SHI	SHPI
T2	1.0	0.11*	–0.04*	–0.14*	–0.52	–0.17*
RH2		1.0	–0.61	–0.52	–0.22	0.47
WS10			1.0	0.79	0.28	–0.38
BLH				1.0	0.48	–0.27
SHI					1.0	0.05*
SHPI						1.0

*Correlation coefficient is not significant at the 95% confidence level.

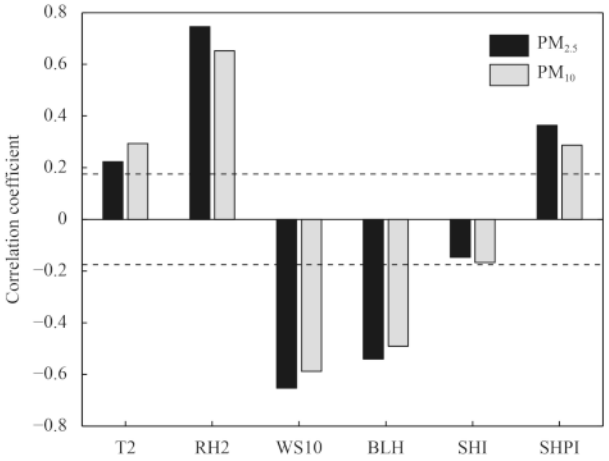

Fig. 3. Correlation between PM concentrations and meteorological parameters in December 2013–16 in the JJJ area. The dashed lines indicate statistical significance at the 95% confidence level, based on the *t*-test.

previous studies (Tai et al., 2010; Jia et al., 2015; He et al., 2017a; Liu et al., 2017). The correlation coefficients were significant at the 95% confidence level, except the SHI. Basically, the correlations between meteorological parameters and $PM_{2.5}$ were higher than those with PM_{10}, except for T2 and SHI.

Table 3 shows the monthly meteorological parameters for December 2013–16 over the JJJ area. When the winter monsoon was strong (high SHI), prevailing northwesterly winds are favorable for the dispersion and transport of pollutants, resulting in good air quality in the JJJ area. The winter monsoon was strongest in December 2014, according to the SHI. A relatively high (low) SHI (SHPI) was responsible for the low $PM_{2.5}$ and PM_{10} concentrations in December 2014. Based on the local meteorological conditions, T2 and RH2 were abnormally low and WS10 and BLH were abnormally high in December 2014. These abnormal meteorological conditions resulted in low concentrations of $PM_{2.5}$ and PM_{10}. With high T2 and RH2, and low WS10 and BLH, the meteorological conditions were more adverse for pollutant dispersion in December 2015 and 2016 than in December 2013 and 2014. However, the concentrations of $PM_{2.5}$ and PM_{10} in December 2015 and 2016 were lower than in December 2013 (Table 1), which implies that control measures have resulted in an effective improvement in air quality.

Table 3. Monthly mean meteorological parameters in December over the JJJ area

	2013	2014	2015	2016
T2 (K)	270.4	269.7	271.3	271.8
RH2 (%)	48.1	39.8	63.4	63.6
WS10 (m s^{-1})	2.8	3.3	2.7	2.4
BLH (m)	406.5	548.5	404.7	305.9
SHI (hPa)	1027.3	1031.0	1025.5	1025.0
SHPI	100.7	101.7	104.8	104.7

The ratio of fine PM to coarse PM ($PM_{2.5}/PM_{10}$) increased year by year, except in December 2014 (Table 1), when it was affected by meteorological conditions and emissions. The average wind speed was higher than 3.2 m s^{-1} in December 2014, which enabled the formation of local dust and sand storms, and the weather phenomena of floating dust was recorded (for December 2014 only). This resulted in a relatively low ratio of fine to coarse PM (Table 1). The increasing RH2 had an adverse influence on visibility under the same loading of PM, and it promoted the formation of secondary PM from gaseous species (Liu et al., 2017). High RH2 (> 60%) is an important factor for understanding the large ratio of fine to coarse particles recorded in December 2015 and 2016 (Table 1). Control measures, such as road watering and covering construction sites, decrease dust emissions (coarse particles). This is another reason for the increase in the ratio of fine to coarse particles in recent years.

Air quality in northern China is prominently correlated with pressure systems (Chen et al., 2008). Six circulation types were identified in this study using the *T*-mode PCA method combined with *K*-means clustering method (Fig. 4). The mean SLP for the six circulation types implied that a strong cold air process with a large pressure gradient controlled the JJJ area for CT1, followed by CT2 and CT3. Static weather with a negligible pressure gradient controlled the JJJ area for CT4 and CT6. The concentration anomalies of $PM_{2.5}$ and PM_{10} (daily mean concentration minus monthly mean concentration) for the six circulations types are shown in Fig. 5. A strong cold air process is beneficial for the rapid dispersion and transport of pollutants, and the lowest concentrations of $PM_{2.5}$ and PM_{10} were detected in CT1, followed by CT2 and CT3. In other words, the concentration anomaly is a positive value for static weather, which indicates that the weather adversely affects the dispersion and transport of pollutants. For CT5, a low-pressure system was located in Northeast China, resulting in southerly winds in the JJJ area that formed serious air pollution due to regional transport and convergence.

The occurrence frequencies of the six circulation types are exhibited in Table 4. The ratios of static weather (CT4 and CT6) to CT5 were 41.9%, 32.3%, 48.4%, and 54.8% in December 2013–16, respectively. The average ratio of static weather to CT5 in December 2013–16 was 44.4%. The good air quality recorded in December 2014 (Table 1) was most likely caused by a high ratio of cold

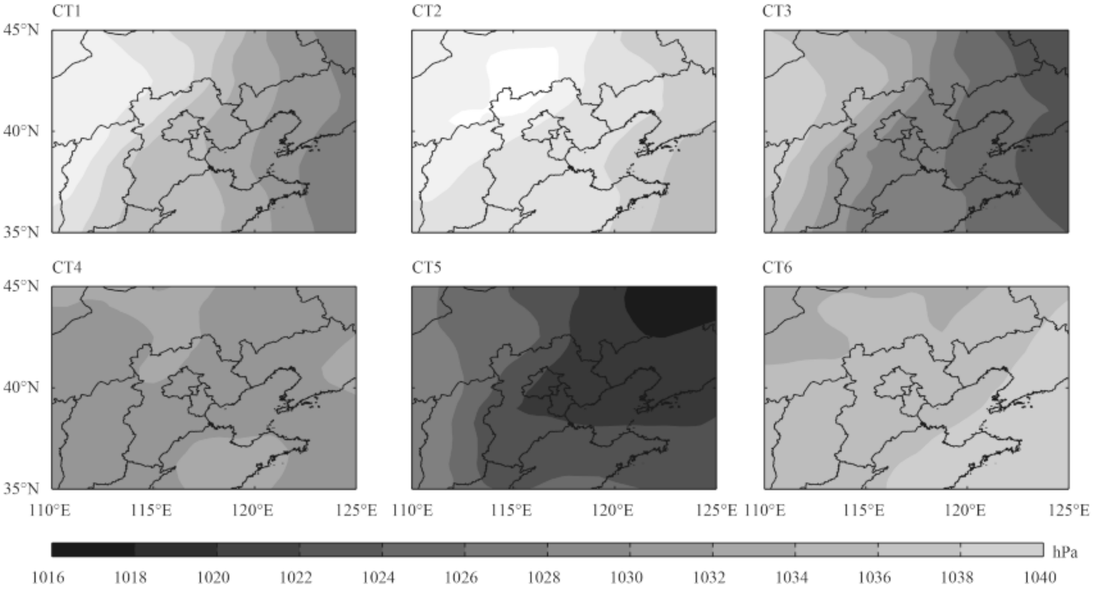

Fig. 4. Mean SLP for the six circulation types during each December from 2013 to 2016.

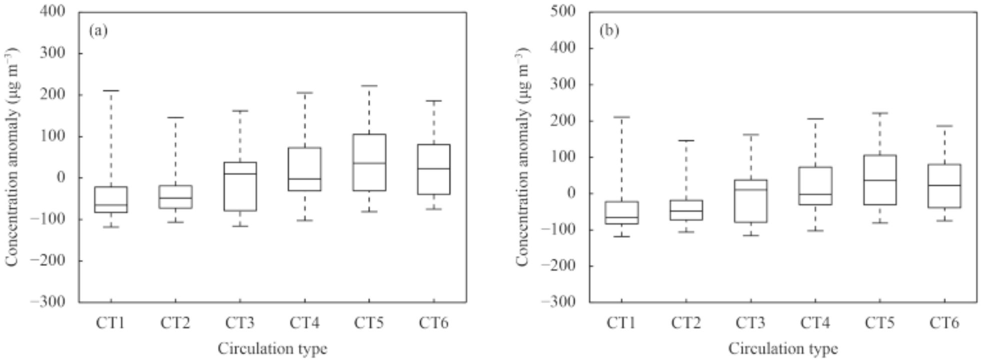

Fig. 5. Box plots of concentration anomalies of (a) $PM_{2.5}$ and (b) PM_{10} for the six circulation types.

Table 4. Occurrence frequencies (%) of the six circulation types in December

	CT1	CT2	CT3	CT4	CT5	CT6
2013	12.9	32.3	12.9	3.2	35.5	3.2
2014	41.9	12.9	12.9	9.7	12.9	9.7
2015	12.9	19.4	19.4	19.4	12.9	16.1
2016	12.9	16.1	16.1	35.5	9.7	9.7
2013–16	20.2	20.2	15.3	16.9	17.7	9.7

air. While poor air quality was recorded in December 2015 and 2016, this was most likely caused by a high ratio of static weather. These data indicate that the interannual variations of meteorological conditions determine the interannual variations of pollutant concentrations during winter.

3.3 *Impact of emissions changes*

Numerical simulation is an important method to identify emissions changes based on the difference between the observed and simulated PM concentration change (using the same emissions inventory) in different years (Yang et al., 2016; Liu et al., 2017). The Chinese Unified Atmospheric Chemistry Environment (CUACE) model coupled with the fifth-generation Penn State/ NCAR mesoscale model (MM5) was used in this study. The model settings, initial and boundary conditions, meteorological forcing fields, and emissions inventory, were consistent with previous studies (He et al., 2016d, 2017b; Liu et al., 2017). The performance of MM5–CUACE has been verified in previous research (He et al., 2016d; Liu et al., 2017), and so an evaluation was not performed again here. Table 5 shows the $PM_{2.5}$ concentration change ratio and emissions change ratio over the JJJ area. Because of the same emissions inventory (2013) for December from 2013 to 2016, the simulated concentration change only represents the impact of meteorological conditions. The observed concentration change represents the impact of both meteorological conditions and

Table 5. Observed and simulated $PM_{2.5}$ concentration change ratio and emissions change ratio (%) over the JJJ area

	Observation	Simulation	Emissions change
2014 vs 2013	−32.6	−19.9	12.7
2015 vs 2014	40.3	48.9	8.6
2016 vs 2015	0.9	9.2	8.3

emissions. Therefore, the emissions change ratio can be inferred from the difference between the simulated and observed change ratio.

With the considerable efforts in terms of emissions control, the emissions of $PM_{2.5}$ decrease by 12.7%, 8.6%, and 8.3% for December 2014, 2015, and 2016, as compared with each previous year, over the JJJ area. The $PM_{2.5}$ concentration increases by about 50% in December 2015 compared with 2014 due to the change in meteorological conditions. Moreover, the impact of meteorological conditions on the interannual variation of the monthly mean $PM_{2.5}$ concentration is larger than the impact of the emissions change. It should be noted that the model simulation contains uncertainties, and the inferred emissions changes should be regarded as approximations only.

4. Conclusions

PM pollution characteristics and their relationship to meteorological conditions in recent winters (during the month of December) in the JJJ area were examined in this paper. Local meteorological parameters (T2, RH2, WS10, and BLH), the intensity and position of Siberian high , and circulation types, in December 2013–16, were analyzed. A modelling study was also conducted to investigate the variation in emissions. The concentrations of $PM_{2.5}$ and PM_{10} were found to decrease from the south to the north of the JJJ area.

When compared to December 2013, a significant decrease in the PM concentration was detected in December 2014, with a decrease of 33% and 51% for $PM_{2.5}$ and PM_{10}, respectively. However, increasing PM concentrations appeared in December 2015. The improvement to air quality in December 2014 was mostly due to favorable meteorological conditions, including a high ratio of cold air processes, high wind speed and boundary layer height, and low temperature and relative humidity. Although meteorological conditions in December 2015 and 2016 were more adverse than in December 2013, the concentrations of $PM_{2.5}$ and PM_{10} in December 2015 and 2016 were lower than in December 2013, which implies that control measures have resulted in an effective improvement in air quality. Based on model experiments with the same emissions inventory in December 2013–16, the emissions of $PM_{2.5}$ were found to decrease by 12.7%, 8.6%, and 8.3% for December 2014, 2015, and 2016, respectively, compared with each previous year, over the JJJ area.

This research only covered four Decembers from 2013 to 2016. The influence of meteorology may vary with climate change. New research with a longer period of data coverage is planned, which should depict the long-term trend for haze pollution and the reasons behind changes in haze from the perspective of atmospheric circulation. Emissions control measures have improved air quality substantially, and will continue to reduce pollutant concentrations in the future based on the "Air Pollution Control Action Plan" released by the Chinese government. The combined effect of meteorology and emissions changes is also an important issue. Lastly, the emissions changes were deduced from the differences between the observed and simulated PM concentration change. However, model simulations contain uncertainties, and so the inferred emissions changes should be regarded as approximations only.

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