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Significant Decrease of $PM_{2.5}$ in Beijing Based on Long-Term Records and Kolmogorov–Zurbenko Filter Approach

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ABSTRACT

Severe haze episodes have hit Beijing many times in the past few years, especially the “crazy bad” pollution described by the US Embassy in Beijing. The publication of numerous multimedia reports on the severe haze has increased awareness among the people in China regarding air pollution and $PM_{2.5}$. It is assumed that the severe haze occurred suddenly for unclear reasons. In this context, long-term evaluation of the air pollution in Beijing is necessary. Through hourly and daily $PM_{2.5}$ concentration records, meteorological datasets from August 2004 onward, and the Kolmogorov–Zurbenko (KZ) filter approach, the evolutions of the long-term components (or background values) of $PM_{2.5}$ concentrations at an urban and a rural station in Beijing were statistically analyzed, and the possible causes of variation in the trends of these components were evaluated in this study. The long-term components of $PM_{2.5}$ concentrations decreased significantly at both the urban (-3.40 µg m^{-3} y^{-1}) and rural (-1.16 µg m^{-3} y^{-1}) stations. The most serious pollution predominantly occurred in an earlier period than recent years, when little attention was being paid. The decrease in $PM_{2.5}$ concentration was mainly attributed to the reduction in pollutant emission, despite the distinct increase in total energy consumption and motor vehicle use. However, the unfavorable climate changes (i.e., a reduction in wind speed and an increase in relative humidity) reduced the efficiency of atmospheric environmental governance. Because of the unfavorable climate or meteorological changes, the trends of $PM_{2.5}$ reduction derived from the pollutant emission controls have been offset by up to approximately 15% in both urban and rural areas of Beijing during the last decade.

Keywords: $PM_{2.5}$; KZ filter; Haze; Air quality; Beijing.

INTRODUCTION

In January 2013, severe haze hit Beijing and most of eastern China. The US Embassy in Beijing described it as “crazy bad” pollution, according to their air quality monitoring reports. Most Chinese people are aware of the adverse effects of haze pollution and are paying more attention to haze pollution and $PM_{2.5}$ (particulate matter less than 2.5 µm in diameter) (Wang *et al.*, 2014a; Wang *et al.*, 2014b; Zhang *et al.*, 2014; Zhang *et al.*, 2015a; Wang and Chen, 2016). Recently, severe haze pollution has occurred in Beijing on multiple occasions, and Beijing issued the first red alert for heavy pollution during November–December 2015. It remains unclear why the air pollution in Beijing is becoming increasingly serious. Under such a background, haze pollution or air quality (indicated by $PM_{2.5}$ concentration) in Beijing was examined since 2004 using two stations’ $PM_{2.5}$ concentration records, which were obtained from Chinese Meteorological Administration.

Generally, haze pollution can be attributed to pollutants emission to the lower atmosphere from fossil fuel combustion or construction and others concurrent with unfavorable meteorological diffusion conditions. The occurrence of haze pollution is strongly influenced by meteorology, because its factors not only have impacts on the accumulation or diffusion, spread, and regional transport of air pollutants, but also have important impacts on the formation of secondary aerosol, which is generated by complicated physical and chemical reactions (Wang *et al.*, 2012; Jeong and Park, 2013; Ramsey *et al.*, 2014; Sun *et al.*, 2015; Quan *et al.*, 2015; Zheng *et al.*, 2015; Marais *et al.*, 2016). Undoubtedly, the haze pollution in Beijing and its adjacent areas is closely linked to economic activities and urbanization during the last several decades. To evaluate the effectiveness of air quality regulations and improve air quality management efforts, the long-term haze pollution trends should be thoroughly

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examined and understood. However, the strong linkage between weather conditions and pollutant levels can obscure the effects of changing emission levels over time; this linkage may mask long-term trends in pollution concentrations resulting from emissions. Rao *et al.* (1997) argued that process changes resulting from policy or climate changes may be very small and difficult to detect in time series unless they are separated from weather and seasonality. One of the methodologies that could be applied for this purpose is the Kolmogorov–Zurbenko (KZ) filter proposed by Rao and Zurbenko (1994). Many studies have suggested that the KZ filter could be a suitable method to separate meteorology-related time series into different time scales, such as those used for O_3 and other gas pollution concentrations and also for particulate pollution concentrations and climate change and others (Rao *et al.*, 1995; Zurbenko *et al.*, 1996; Eskridge *et al.*, 1997; Lu and Chang, 2005; Wise and Comrie, 2005a, b; Yang and Zurbenko, 2010; Zurbenko and Cyr, 2011; Kang *et al.*, 2013; Zurbenko and Potrzeba, 2013; Edward and Zurbenko, 2014; Elisa *et al.*, 2015; Ma *et al.*, 2016; Li *et al.*, 2017).

In short, the purpose of the study was to examine the long-term trends of haze pollution in Beijing during the last decade based on two long-term record series of $PM_{2.5}$ concentrations and the KZ filter approach and to evaluate the long-term trends of pollutants affected by meteorology and emissions. This paper is organized as follows. The data and methods are described in Section 2. The major results and discussion are presented in Section 3. The conclusions are summarized in Section 4.

MATERIALS AND METHODS

Site Description and Data Collection

Hourly $PM_{2.5}$ concentrations were taken from the urban station at Baolian (BL) and the rural station at Shangdianzi (SDZ), which have been operated by the Chinese Meteorological Administration since August 2004. The SDZ is one of the regional Global Atmosphere Watch (GAW) stations in China, and it is located on the northern North China Plain, in Miyun County of Beijing (Fig. 1). The observation of pollutants at the SDZ reflects the regional-scale air quality of North China (Lin *et al.*, 2008; Ma *et al.*, 2016). From August 2004 to February 2016, the hourly missing data rates for the pollutant records of the BL and SDZ stations were approximately 1.2% and 1.5%, respectively, indicating a great continuity of the monitoring operations. Moreover, $PM_{2.5}$ records from April 2008 onward, which were derived from the US Embassy in Beijing (BUE), were used to predict the missing observations at BL and SDZ stations through regression analysis.

The SDZ station is a conventional meteorological observatory, whereas the BL station monitors air pollutants only. Thus, pollutant data from the BL were compared with meteorological data from the nearest conventional meteorological station (Haidian station, which is 4 km from the BL station) (Zhang *et al.*, 2015b). In the analysis, hourly and daily meteorological datasets, including the mean wind speed, daily maximum wind direction, daily mean temperature, relative humidity, surface pressure, daily precipitation amount, and sunshine hours, of the two stations were used.

Analysis Methods

Common statistical methods, such as least-square regression and Pearson correlation analyses with a two-tailed Student's t-test, were applied in this study. To better understand the long-term trends of pollution concentration and its relation to meteorological variables, a KZ filter (Rao and Zurbenko, 1994) was used to separate daily data into short-term, seasonal, and long-term variations. In this approach, a time series of the daily $PM_{2.5}$ concentration or

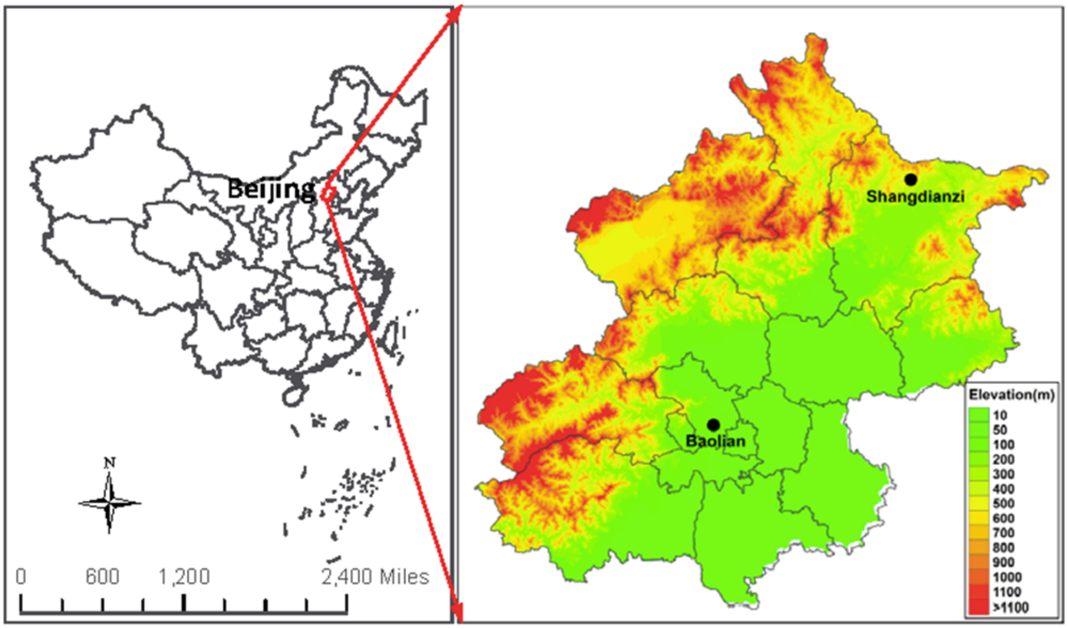

Fig. 1. Locations of the urban station at Baolian (BL) and the rural station at Shangdianzi (SDZ).

meteorological variable data can be represented by

$$O(t) = e(t) + S(t) + W(t) \tag{1}$$

where $O(t)$ is the original time series, $e(t)$ is the long-term trend component, $S(t)$ is the seasonal variation, and $W(t)$ is the short-term (synoptic scale) component. The KZ filter is a low-pass filter produced through repeated iterations of a moving average. The moving average for a $KZ_{(m,p)}$ filter (a filter with window length m and p iterations) is defined by

$$Y_i = \frac{1}{m} \sum_{j=-k}^{k} O_{i+j} \tag{2}$$

where k is the number of values included on each side of the targeted value, the window length $m = 2k + 1$, and O is the input time series. The output of the first pass then becomes the input for the next pass (Milanchus *et al.*, 1998; Wise and Comrie, 2005b). According to the results of Rao *et al.* (1997), when $KZ_{15,5}$ and $KZ_{365,3}$ filters were applied to the raw data, several influences (such as the synoptic and seasonal components) were removed, and the variations of the raw time series at different scales were obtained.

$$W(t) = O(t) - KZ_{15,5} \tag{3}$$

$$S(t) = KZ_{15,5} - KZ_{365,3} \tag{4}$$

$$e(t) = KZ_{365,3} \tag{5}$$

The short-term variation of $PM_{2.5}$ concentration may be attributable to weather conditions and pollutant emissions on a day-to-day time scale. The seasonal component may be a result of the changes in the solar angle, and the long-term component results from changes in emissions, pollutant transport, climate, policy, and economics (Rao and Zurbenko, 1994; Rao *et al.*, 1997; Wise and Comrie, 2005a).

Moreover, in order to understand the long-term trends of $PM_{2.5}$ concentration without the impact of meteorological condition changes, the multiple regression analyses were used to estimate the meteorologically adjusted $PM_{2.5}$ concentrations for both the urban and rural stations. Specifically, a unique multiple regression equation was established for each station based on the observed meteorological factors and $PM_{2.5}$ during the entire period from August 2004 to February 2016. According the regression equation and the meteorological factor records, the meteorologically adjusted $PM_{2.5}$ concentrations for both stations were estimated. The estimated meteorology-related components [$\bar{O}(t)$] were subtracted from the raw $PM_{2.5}$ time series [$O(t)$], and the residuals were regarded as the meteorologically adjusted parts [$O'(t)$]. And then the KZ filter was performed for the meteorologically adjusted $PM_{2.5}$ concentration series.

RESULTS AND DISCUSSION

The original hourly $PM_{2.5}$ concentrations at the BL and SDZ are plotted in Figs. 2(a) and 2(e), respectively (the records from BUE are shown in red lines in the left panel). The short-term, seasonal, and long-term components produced by the KZ filter are given in the second to fourth graphs, respectively. The raw $PM_{2.5}$ records from the different stations were compared. The correlation coefficients between BL–BUE, BL–SDZ, and BUE–SDZ were 0.926, 0.746, and 0.773, respectively. The magnitude of correlations suggested that the $PM_{2.5}$ concentration variability among different stations were consistent with each other during common periods. The mean $PM_{2.5}$ concentrations at the BL, BUE, and SDZ during the covering periods were 77.8, 94.8, and 46.6 $\mu g\ m^{-3}$, respectively. The systematic deviations between BL and BUE were mainly caused by the variation in measuring instruments (TEOM1405 used in BL and METONE1020 used in BUE) and local ambient environments. The low $PM_{2.5}$ at the SDZ was reasonable and reflected the regional background concentration. Thus, the two long-term datasets of $PM_{2.5}$ concentrations in urban and rural Beijing were reliable and valuable for studying the evolution of haze pollution in Beijing from a long-term perspective. For discussing the changes over a longer time span, only the $PM_{2.5}$ records from BL and SDZ were analyzed.

Intuitively, intense day-to-day variability can be seen in the original and short-term curves at all stations. Calculations using the KZ filter show that the short-term component had the highest contribution to the total variance of the original $PM_{2.5}$ data: 85.1% for BL and 83.4% for SDZ. The seasonal components (Figs. 2(c) and 2(g)) at both the urban and rural stations reflected the winter–summer cycle, which is closely linked to the meteorological conditions and human activity such as the considerable energy consumption (coal and gas) during the central heating period in northern China. The long-term component of $PM_{2.5}$ concentration decreased distinctly at both stations during the most recent decade, although some fluctuations were also observed. The linear trends of the long-term components of $PM_{2.5}$ concentration at the BL and SDZ were –3.40 $\mu g\ m^{-3}\ y^{-1}$ and –1.16 $\mu g\ m^{-3}\ y^{-1}$, respectively. In theory, the changes in the long-term $PM_{2.5}$ concentration may be roughly attributed to two aspects, namely pollutant emission and climate change. A previous study demonstrated that seven meteorological factors (wind speed, wind direction, temperature, relative humidity, pressure, precipitation, and sunshine hours) could explain approximately 50%–60% of variance in the winter daily $PM_{2.5}$ concentrations in Beijing. Moreover, the explained variances in spring and autumn were generally less than those in winter and larger than those in summer (Zhang *et al.*, 2015b). During the entire evaluation period, the explained variances were approximately 17.4% and 26.7% of the daily $PM_{2.5}$ at the BL and SDZ, respectively. Thereafter, the short-term, seasonal, and long-term components of the meteorologically adjusted $PM_{2.5}$ [$O'(t)$] were separated through the KZ filter. The results showed that the change trends of the long-term component of the meteorologically adjusted $PM_{2.5}$ were highly consistent with those of the raw time series for both the urban and rural stations (Fig. 3). The linear trends of the long-term components of the meteorologically adjusted $PM_{2.5}$ series for BL and SDZ

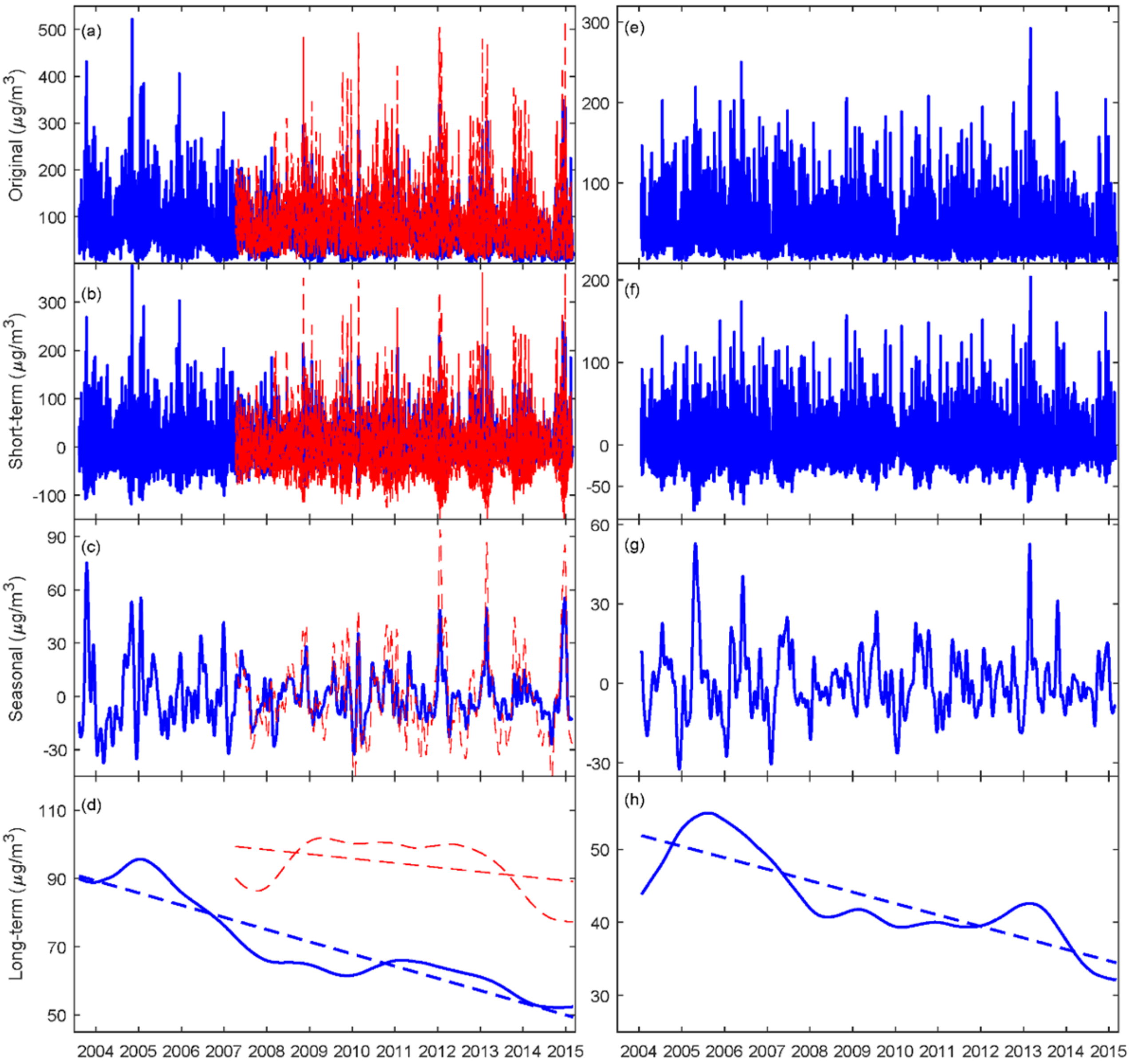

Fig. 2. Original (a), short-term (b), seasonal (c), and long-term (d) components of the daily $PM_{2.5}$ concentrations at BL (blue line) and BUE (red) are shown in the left panel; the right panel shows the concentrations at SDZ (the dashed straight lines in d and h denote the linear trends).

were –4.02 μg m^{-3} y^{-1} and –1.38 μg m^{-3} y^{-1}, respectively. Notably, the linear trends of the long-term component of the meteorologically adjusted $PM_{2.5}$ concentrations were greater, on average, than those of the original $PM_{2.5}$ time series for both stations. Specifically, the negative linear trends of meteorologically adjusted $PM_{2.5}$ at the BL and SDZ increased by 18.24% ((4.02–3.40)/3.40 × 100) and 18.97% ((1.38–1.16)/1.16 × 100), respectively, compared with the original $PM_{2.5}$ time series. These results suggest that the meteorological factors were not conducive to the reduction of $PM_{2.5}$ concentrations of both urban and rural areas during the last decade. In fact, this computation suggests that the effects of atmospheric environmental governance in Beijing and adjacent areas (i.e., industrial emission controls, motor vehicle restrictions, improvements of energy utilization technology, and optimizations of energy structures) were offset by up to 15.42% ((4.02–3.40)/4.02 × 100) in urban areas and 15.94% ((1.38–1.16)/1.38 × 100) in rural areas because of unfavorable meteorology changes.

Details regarding the most important meteorological factors for air pollution, such as wind speed and relative humidity, were unclear. Therefore, the evolution of the long-term components of wind speed and relative humidity for both BL and SDZ were also examined through the KZ filter. The long-term components of wind speed (or relative humidity) at both urban and rural areas decreased (or increased) significantly during the entire period, although some inter-annual fluctuations also existed, especially for the relative humidity (Fig. 4). The linear trends of the long-term components of wind speed (relative humidity) were

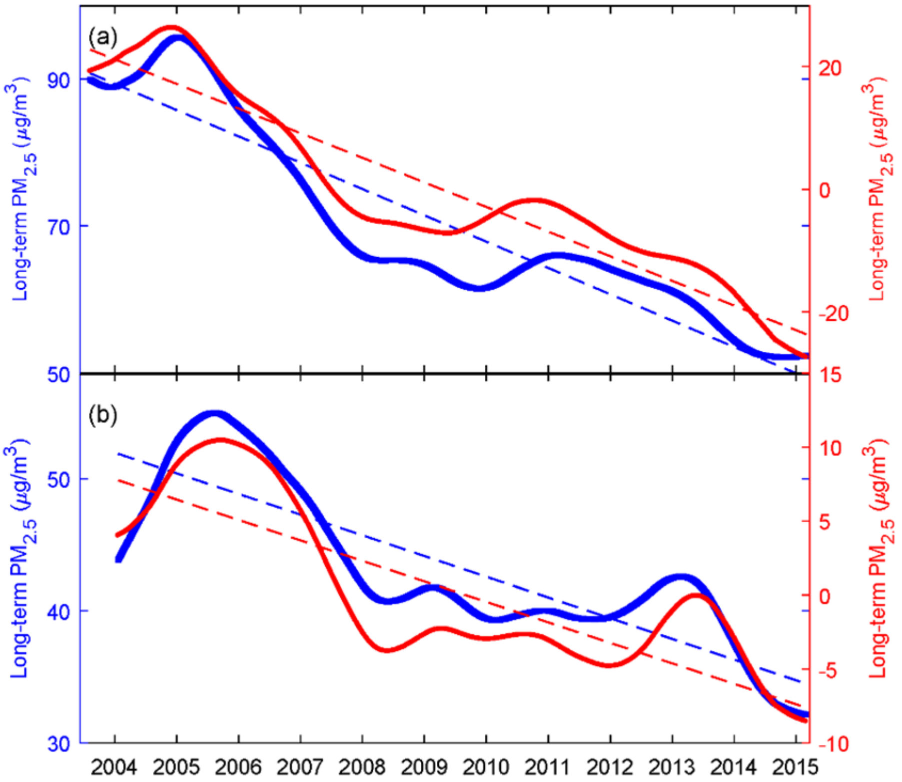

Fig. 3. Long-term components of the raw $PM_{2.5}$ (blue line) and the meteorologically adjusted $PM_{2.5}$ (red line) for the urban station at BL (a) and the rural station at SDZ (b) (the dashed straight lines denote the linear trends).

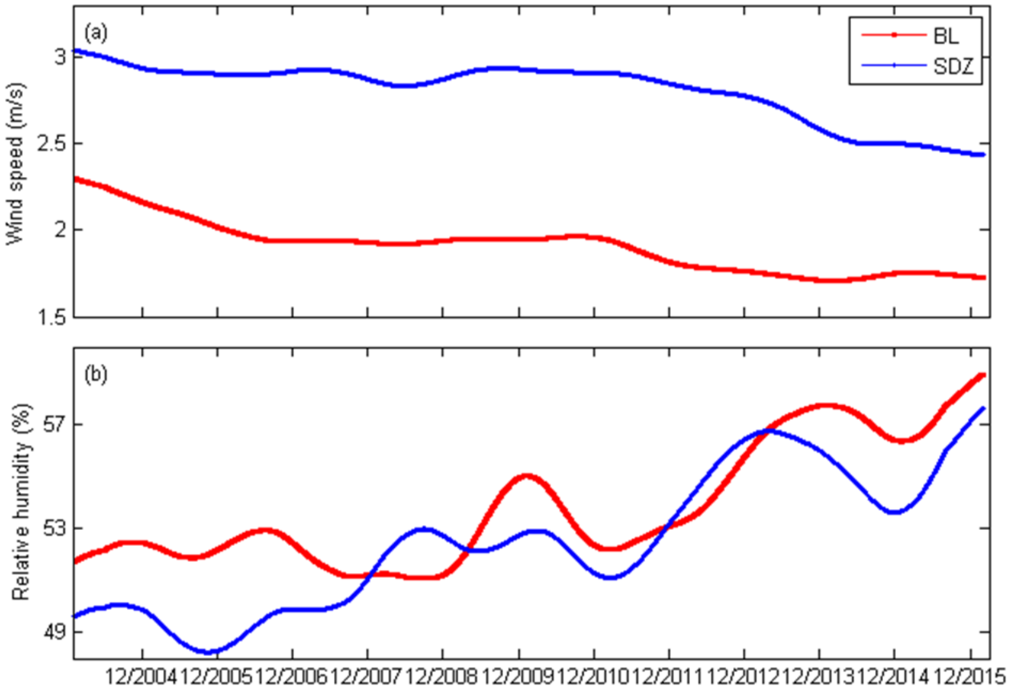

Fig. 4. Long-term components of wind speed (a) and relative humidity (b) at the urban station of BL (red line) and the rural station of SDZ (blue line).

–0.039 m s^{-1} y^{-1} (0.539 % y^{-1}) and –0.040 m s^{-1} y^{-1} (0.651 % y^{-1}) at BL and SDZ, respectively. Decreasing wind speed is not conducive to the diffusion of air pollutants and often leads to haze pollution in Beijing. Furthermore, high relative humidity is favorable for the accumulation and hygroscopic growth of pollutants, which can strengthen the scattering and absorption of light by atmospheric particles and gases, thus degrading visibility and increasing air pollution concentration (Baumer *et al.*, 2008; Zhang *et al.*, 2016).

On the other hand, assuming that the pollutant emissions around Beijing and its adjacent areas remained nearly constant for the last several decades, the $PM_{2.5}$ concentration in both the urban areas and regions around Beijing should have increased due to the unfavorable climate changes (weakened wind speed and increased relative humidity). However, the results determined through $PM_{2.5}$ records from multiple sources and the KZ filter approach did not support this hypothesis. Thus, the decrease of the long-term component of $PM_{2.5}$ concentrations should mainly be attributed to the reductions in pollutant emission in Beijing and its adjacent areas or even to reductions in pollutant emission in northern China. From the records in the statistical yearbooks of China and Beijing, graphs of the annual total energy consumption, motor vehicle use, SO_2 emission, SO_2 concentration, and NO_2 concentration in Beijing since 2004 are shown in Fig. 5. Intuitively, the total SO_2 emission and the mean SO_2 and NO_2 concentrations in Beijing have decreased distinctly since 2004 (an anomalous low NO_2 concentration was observed in 2008 due to the strict pollutant emission controls leading up to the 2008 Beijing Olympics), despite the simultaneous increase in the total energy consumption and motor vehicle use. According to satellite data, Liu *et al.* (2016) also demonstrated that the NO_x emissions over Beijing and most of China have been reduced significantly during the past decade. In view of the improvements in energy utilization technology and optimizations of energy structures (e.g., the burning of gas instead of coal in a central heating supply), the increase in the total energy consumption does not imply an increase in pollutant emission. Undoubtedly, the reduction in pollutant emission was the primary cause for the decrease in $PM_{2.5}$ concentration over the last decade, even though the unfavorable climate changes depressed the efficiency of atmospheric environmental governance.

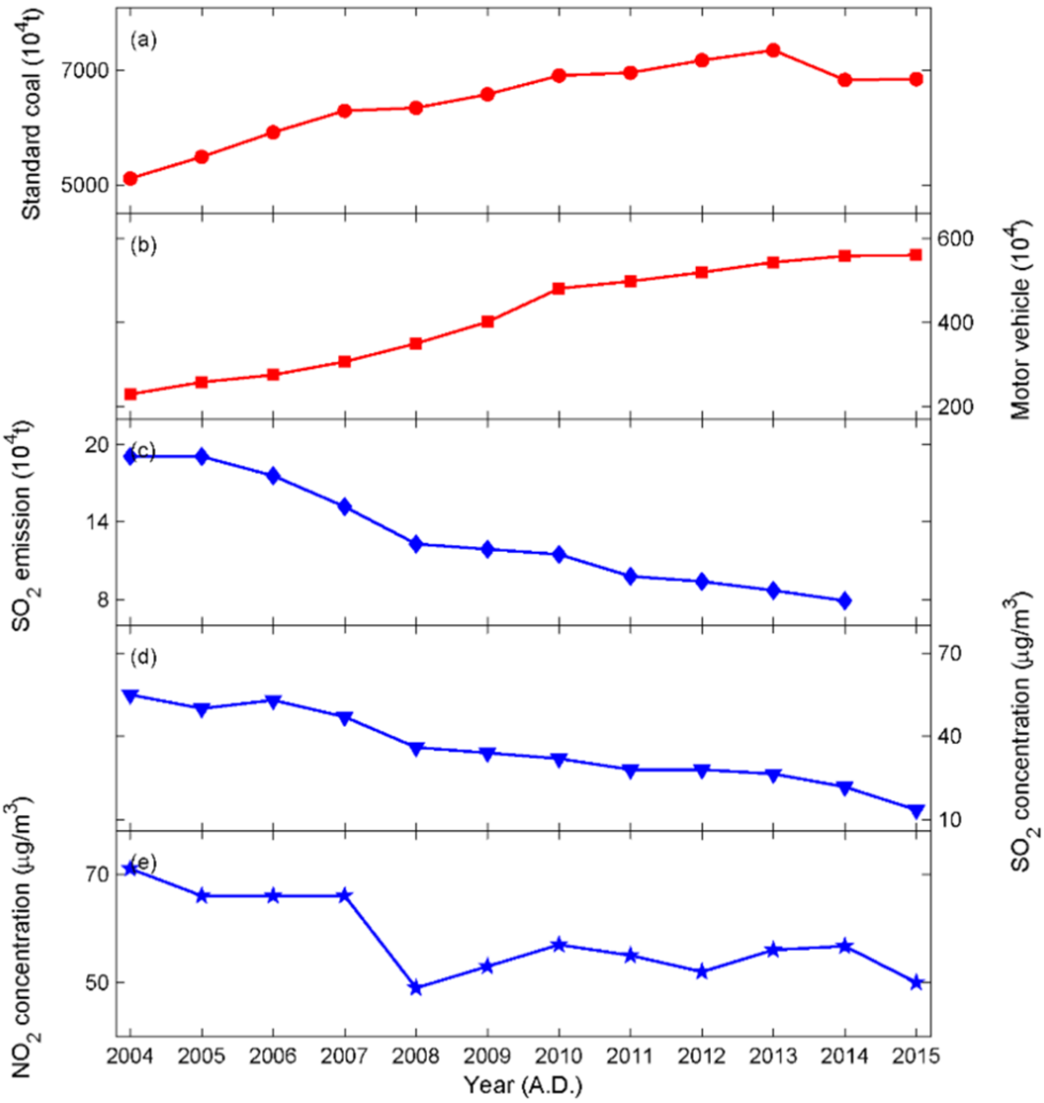

Fig. 5. Total energy consumption (a), motor vehicle (b), SO_2 emission (c), SO_2 concentration (d), and NO_2 concentration (e) in Beijing.

CONCLUSIONS

The main conclusions can be summarized as follows. (1) The $PM_{2.5}$ concentration decreased significantly at both the urban and the rural stations, and the linear trends of the long-term components for BL and SDZ were –3.40 µg m^{-3} y^{-1} and –1.16 µg m^{-3} y^{-1}, respectively. The results indicated that the severe pollution did not occur suddenly or recently. To the contrary, the most serious pollution events happened during an earlier period, and too little attention was given to early haze pollution in Beijing and its adjacent regions. (2) The decrease in the $PM_{2.5}$ concentration was mainly attributed to a reduction in pollutant emissions, despite the increase in total energy consumption and motor vehicle use. (3) The unfavorable climate changes (i.e., reduction in wind speed and increase in relative humidity) depressed the efficiency of atmospheric environmental governance. Because of the unfavorable climate or meteorological condition changes, the trends of $PM_{2.5}$ concentration reduction caused by the pollutant emissions controls were offset by up to approximately 15% in both urban and rural areas of Beijing during the last decade.

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