and 46.6 μg 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. 2c and 2g) 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 μg m^{-3} y^{-1} and −1.16 μg 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 (Z.Y. Zhang *et al.*, 2015). 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 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 -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.

CONCLUSIONS

The main conclusions can be summarized as follows. (1) The $PM_{2.5}$ concentrations decreased significantly at both the urban and 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 were in the early 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 reductions 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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Figure Captions

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

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).

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

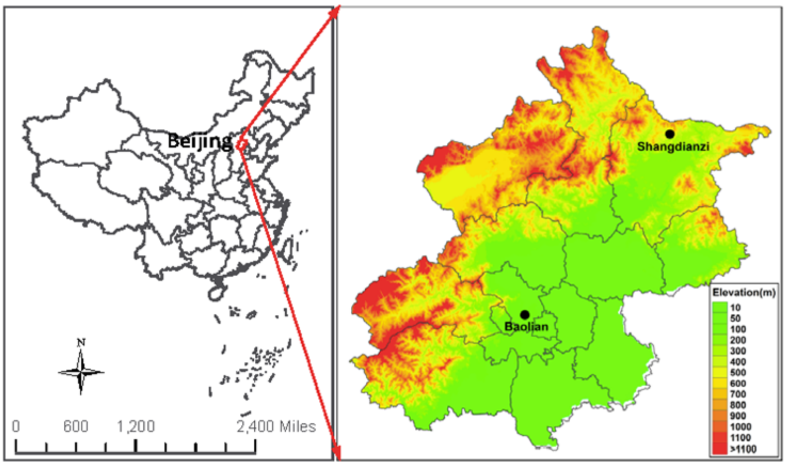
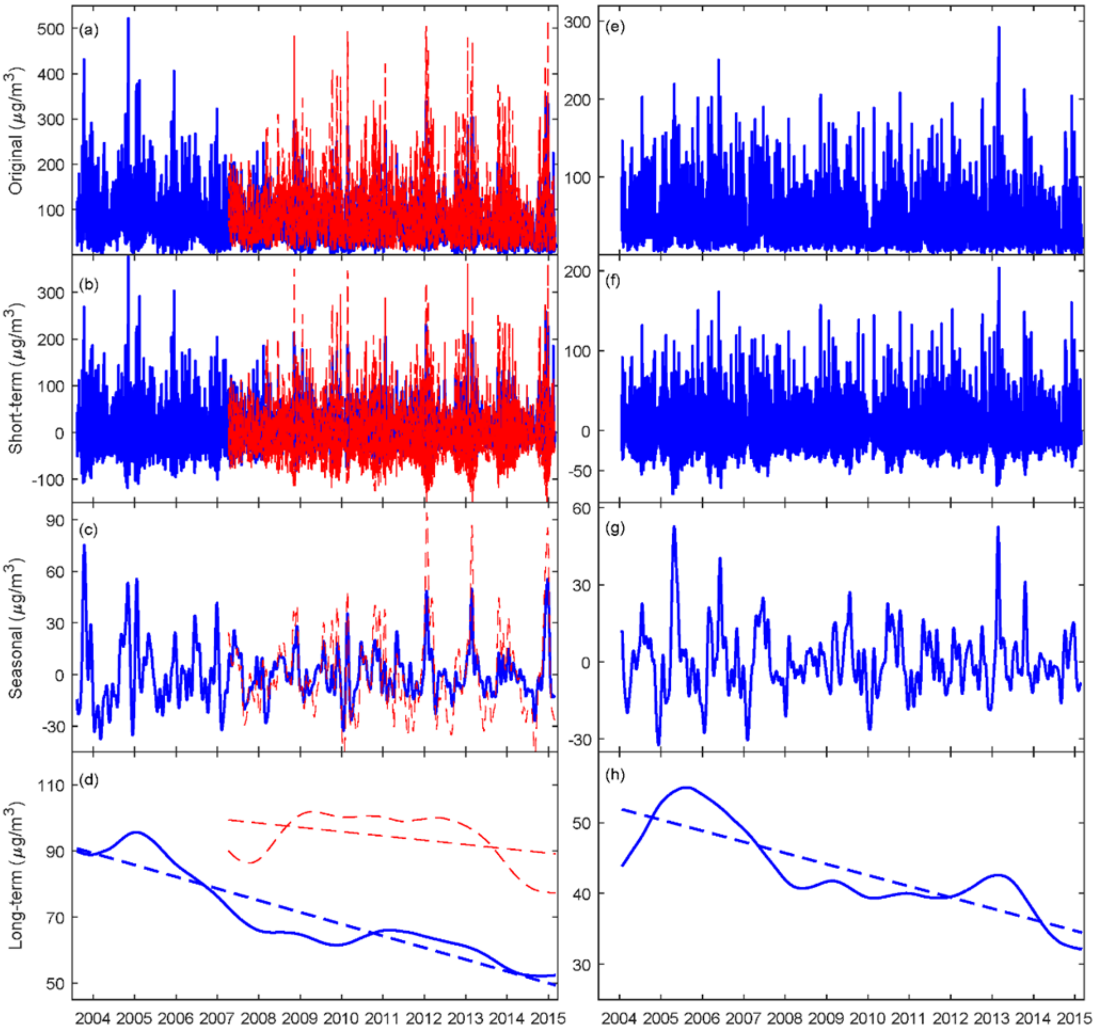


Fig. 1.



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Original (μg/m^3)
Short-term (μg/m^3)
Seasonal (μg/m^3)
Long-term (μg/m^3)
500
400
300
200
100
300
200
100
0
-100
90
60
30
0
-30
110
90
70
50
300
200
100
200
100
0
-50
60
30
0
-30
50
40
30
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Fig. 2.

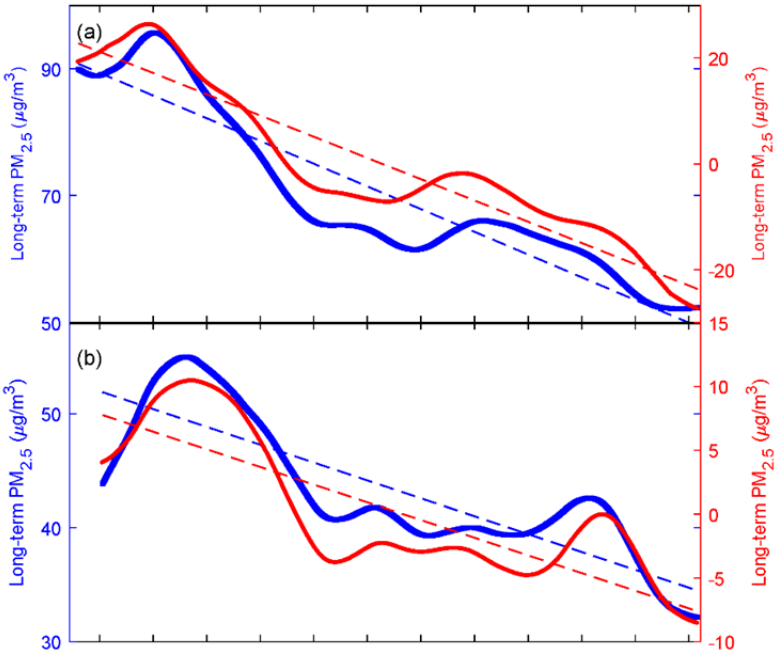

(a)
(b)
Long-term PM$_{2.5}$ (μg/m^3)
90
70
50
40
30
20
0
-20
15
10
5
-5
-10
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

Fig. 3.

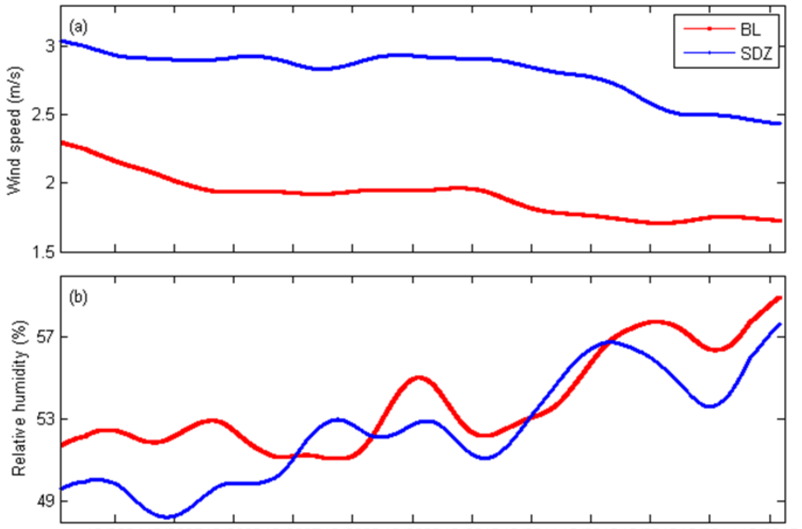

(a)
BL
SDZ
Wind speed (m/s)
3
2.5
2
1.5
(b)
Relative humidity (%)
57
53
49
12/2004
12/2005
12/2006
12/2007
12/2008
12/2009
12/2010
12/2011
12/2012
12/2013
12/2014
12/2015

Fig. 4.

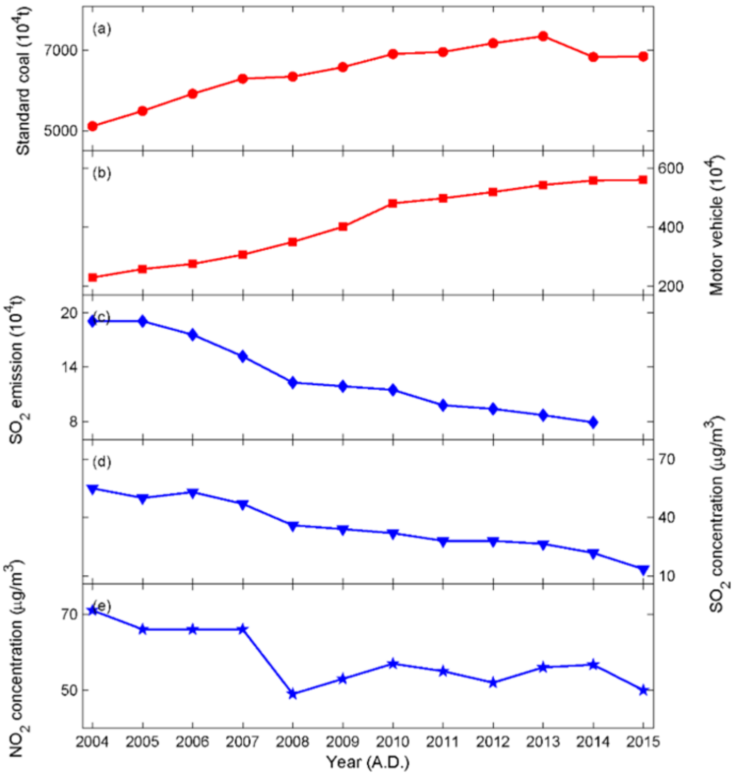

(a)
(b)
(c)
(d)
(e)
Standard coal (10^4t)
7000
5000
Motor vehicle (10^4)
600
400
200
SO$_2$ emission (10^4t)
20
14
8
SO$_2$ concentration (μg/m^3)
70
40
10
NO$_2$ concentration (μg/m^3)
70
50
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year (A.D.)

Fig. 5.