Re-evaluating the variation in trend of haze days in the urban areas of Beijing during a recent 36-year period

Zuofang Zheng1,2,3 | Yingxin Li4 | Hong Wang2 | Haiyan Ding3 | Yubin Li2 | Zhiqiu Gao2 | Yuanjian Yang2

1Institute of Urban Meteorology, China Meteorological Administration, Beijing, China
2School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing, China
3Environmental Meteorology Forecast Center of Beijing-Tianjin-Hebei, China Meteorological Administration, Beijing, China
4Climate Research Center, Chinese Research Academy of Environmental Sciences, Beijing, China

Correspondence
Yuanjian Yang, School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China.
Email: yyj1985@nuist.edu.cn; yyj1985@mail.ustc.edu.cn
Zhiqiu Gao, School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing 210044, China.
Email: zgao@nuist.edu.cn

Funding information
Missions of the Ministry of Science and Technology of China, Grant/Award Number: 2016YFC0203300 and 2017YFC1502104; Beijing natural science foundation, Grant/Award Number: 8171002; National Natural Science Foundation of China, Grant/Award Number: 41575010, 41575003, 41601550, 41505004, and 41675009

1 | INTRODUCTION

The recent increase in haze pollution in China has strongly affected the health of the population, which is mainly the result of the increasing amount of emissions as the population increases and the economy grows rapidly, combined with poor diffusion conditions (Guo et al., 2011, 2016; Liu et al., 2013; Jiang et al., 2015; Liu et al., 2015; Wang and Chen, 2016; Yang et al., 2018). Air quality has a significant influence on both social and economic development, public health, and climate change (Huang et al., 2014; Li et al., 2016; Gu et al., 2018; Hu et al., 2018; Wang et al., 2019).

By using meteorological station data, the inter-annual variability of haze days and its trends are re-evaluated in the urban areas of Beijing during a recent 36-year period. Observations from station 54,511, which is a national reference climatological station in the urban area of Beijing, are not suitable for representing the whole urban area, since it trends oppositely to the surrounding stations. Instead, averaged haze days according to five stations in the urban area of Beijing were selected representatively, illustrating that haze days have a positive trend during the period 1980–2015, and haze occurs more often in autumn and winter than in spring and summer. Notably, the number of haze days has increased more rapidly in summer than in the other three seasons. Severe and persistent haze days exhibit positive trends of 4.1 and 13 days/decade, respectively, during the investigation period, while the corresponding ratios to the total haze days have also increased gradually. The haze in Beijing has also become more severe and drier. Under the weakening East Asian monsoon in winter, there has been a reduction in days of locally strong wind speeds and rain, and an increase in days of weak wind speeds. This has directly contributed to the weakening of the diffusion of pollutants, which would otherwise act to maintain the haze, thus prolonging the duration of haze pollution days in urban areas of Beijing.

KEYWORDS
Beijing, haze events, inter-annual variability, long-term trends, representative station
determine the pollutant diffusion, depending on the wind speed, wind direction, relative humidity, assuming pollutants are released steadily (Ding and Liu, 2013; Zhang et al., 2014). In addition, inter-annual variability and the long-term trend of heavy haze pollution are sensitive to the nature of the local and large-scale circulations (Che et al., 2009; Ji et al., 2012; Chen and Wang, 2015; Miao et al., 2015a, 2015b, 2017; Cai et al., 2017; Zheng et al., 2018). Therefore, for the establishment of observationally long-term variations and trends of haze days, it is important that a reference observation station is suitably selected to explore the haze trend and its relationship with climate variability.

In recent years, Hu and Zhou (2009) and Wu et al. (2014) found a negative trend of haze days from 1980 to 2005 based on the data of station 54,511, which is a national reference climatological station in the urban areas of Beijing. However, this differs from the trend in the whole BTHR (Zhang et al., 2015; Ding et al., 2017). Therefore, it is necessary to investigate whether the trend in Beijing truly differs from the whole region, or whether this inconsistency results from artifacts in the data. The primary goals of this paper are to substantiate this controversy and determine the intrinsic nature of the long-term and inter-annual variability of haze in the urban areas of Beijing.

2 | DATA AND METHOD

Daily data of meteorological stations in Beijing, Tianjin, Langfang, and Tangshan from 1980 to 2015 are analyzed, which measure the relative humidity, visibility, wind speed, precipitation, and other meteorological variables. All data were provided by the Beijing, Hebei and Tianjin Meteorological Information Centers. Here, the East Asian winter monsoon (EAWM) index is defined by the mean geopotential height at 500 hPa in the area of (25°-45°N, 110°-145°E) to describe the East Asian trough (EAT) intensity, which is closely associated with the EAWM and cold activity (Wang and He, 2012; Wang et al., 2015); the larger the value of EAWM index, the weaker the EAWM. The annual energy consumption data in Beijing is obtained from the Bureau of statistics of Beijing (http://www.bjstats.gov.cn/).

There are two common methods to define a haze day (Schichtel et al., 2001; Doyle and Dorling, 2002; Che et al., 2009; Wu et al., 2010). One definition of haze (hereafter refer to daily-average method) is when the daily average visibility and relative humidity are less than 10 km and 90%, respectively, excluding natural events such as precipitation, dust, fog, mist, and gales using the present weather code. The second definition (hereafter refer to 14-hr method) is based on the observation at 1400 local time instead of a daily average, because the midday values are more representative of the regional visibility levels, as early morning radiation fog and the high relative humidity, which may reflect only local conditions, would have mostly dispersed by midday (Lee, 1990; Doyle and Dorling, 2002; Che et al., 2009; Wu et al., 2010). For instance, Zhao et al. (2011a, Zhao et al., 2011b) compared these two methods, and concluded that the latter is better for haze-day identification, especially for large regions and a long temporal analysis.

Therefore, the 14-hr method is used here for the analysis on the variation in trend of haze days in the urban areas of Beijing during a recent 36-year period. Additionally, a severe haze day is defined as a day with a visibility <3 km, and continuous haze days refers to haze lasting more than 2 days according to the observational criteria from the China Meteorological Administration (QXT 113-2010). A mixed haze-and-fog day is referred to as a day of relative humidity of 80 to 95%, and a visibility of less than 10 km, excluding natural events.

3 | RESULTS

3.1 Selection of representative sites

Of the 20 meteorological stations in the Beijing area (Figure 1a), one station (54511) serves as the national reference climatological station and is usually also used as the representative of this area. Since 1980s, there have been two relocations at the 54,511 station:

1. It was moved from suburb area (39.80°N, 116.47°E) to urban area (39.94°N, 116.30°E) on January 1, 1981, when its surrounding environment and underlying types had been changed significantly.
2. On April 1, 1997, it was moved back to the original site (39.80°N, 116.47°E).

Figure 1b shows a negative trend of haze days of 25.9 days/decade during the period from 1980 to 2015 according to data from station 54,511. In contrast, the average number of haze days according to the other 19 stations gives a positive trend of 11.1 days/decade in the same period. However, energy consumption, which is to some degree an indicator of pollutant emissions, has risen exponentially since 1980, and is negatively correlated with the number of haze days observed at station 54,511 (correlation coefficient: r = −0.75, p < 0.01).

The correlation between the haze days in Beijing and other cities nearby is shown in Table 1, which are cities with similar pollutant emissions, and possess the same climatic conditions. At station 54,511, haze days are negatively correlated with those observed at the Tianjin, Langfang, and Tangshan stations. In contrast, the average number of haze days at the other 19 stations in Beijing has a positive correlation with the three aforementioned stations, which means these stations display the same positive trend for the number of haze days. Such trends are consistent with previous studies in northern China, and even eastern China, where the
number of haze days indicates the same positive tendency (Song et al., 2013; Zhang et al., 2015; Ding et al., 2017). Thus, the observations at station 54,511 are not suitable to represent the variation in the number of haze days in Beijing.

According to the definition of a haze day, the relative humidity observed at station 54,511 is slightly lower than that averaged from the other 19 stations in Beijing, with both varying consistently (Figure 2a). Nonetheless, the visibility from the above two datasets is quite different, showing the opposite trends before 2005 (Figure 2a). As station 54,511 has been moved two times since 1980, which probably caused the inhomogeneous series of visibility and relative humidity at different locations throughout the studied period (Li and Yan, 2009; Yan et al., 2010; Zheng and Ren, 2018), it is invalid to use observations at station 54,511 to represent the variations in haze days in the Beijing area.

Referring to empirical orthogonal functional analysis (Ren et al., 2008), and excluding the stations moved two times or above since 1980, or those located over 300 m above the sea level, we finally chose the stations FS, SY, HD, SJS, and DX as the reference urban stations from other 19 stations (see Figure 1a), and then calculate their average haze days as be representative value of the Beijing urban area. In addition, the SDZ station with no relocation history is selected as a rural station since it is far from the sources of urban pollutants and is the only suitable station for a background reference in northern China. The correlations of haze days between the average of the five stations and those stations at Tianjin, Langfang, and Tangshan are 0.79, 0.79, 0.85, respectively, and the average number of haze days of the five stations is highly correlated (0.78) to the energy consumption of Beijing. The SDZ rural station has a greater correlation to the stations at the aforementioned three cities (0.63, 0.62, and 0.79, respectively). Therefore, the analysis...
of haze days based on the average of the aforementioned five stations with respect to the SDZ rural station would be a more reasonable approach.

### 3.2 Urban–rural difference in haze days

Figure 2b shows the number of haze days from the urban and rural stations to illustrate the consistent positive trend from 1980 to 2015. Comparing the number of haze days from urban and rural stations, haze days are significantly more frequent in the urban than the rural area each year (Figure 2b), with the difference varying from 10 days (in 1985) to 74 days (in 2006). Also evident is a significant drop in the number of haze days since 2007, and the urban–rural differences have been in decline, which is mainly the result of emission-reduction measures in Beijing (such as coal gasification, the relocation of high-polluting industries, and limiting the purchases of cars) for the Beijing Olympic Games in 2008 (Zhang et al., 2009). However, the number of haze days has started to rise again in recent years and has reached the level before the Olympics in the last 5 years. Additionally, the change rate of urban haze days is 15.8 days/decade, which is significantly more than the rural rate (11.9 days/decade). Such differences are probably the result of the increased amount of pollutants produced in urban areas than in rural areas. In particular, the decrease in the urban–rural difference during the 2008 Olympic Games emission-reduction program also shows that local emission-reduction efforts can still prove beneficial. Notably, comparing with the daily-average method, here as the 14-hr method is used to reconstruct haze days in Beijing area, it will underestimate the number of haze days, but it can still reflect the long-term trends of haze days (Zhao et al., 2011a, 2011b).

### 3.3 Inter-annual variation in seasonal haze days

Figure 3 presents the inter-annual variation in haze days and their trends for each of the four seasons. In spring (March–
May), summer (June–August), autumn (September–November), and winter (December–February), the average numbers of haze days in Beijing are 9.7, 11, 16.5, and 15.9 days, respectively, accounting for 17.8, 19.6, 31.7, and 30.9% of the haze days over an entire year, implying haze occurs more frequently in autumn and winter than in spring and summer. The differences in seasonal haze days can be explained as follows: because Autumn and winter are traditional heating and coal-burning seasons in northern China, the haze days in autumn and winter are relatively higher because of the concentrated population and the consequent increased energy consumption and unfavorable meteorological conditions (Cai et al., 2017; Pei et al., 2018; Yang et al., 2018; Zheng et al., 2018). While the lower haze days in spring are closely related to the large average wind speed and more windy days during this period, and those in summer are mainly corresponding to more wet deposition of precipitation (Miao et al., 2015b; Zheng et al., 2018). Over the investigated period, there is a positively increasing trend in each season, while the trends in the percentages of haze days in each of the four seasons are distinctive. There is no obvious trend in percentages in spring (Figure 3a); in summer, there is a positive trend with the rates of 4.1 and 4.3%/decade from 1980 to 2015 (Figure 4a). Recently, continuous haze days occur more frequently, and have gained significant attention among citizens. For instance, haze in the Beijing–Tianjin–Hebei region continued for about 1 week in January 2013, representing one of the severest air-pollution events in the recent 5 years. Figure 4b shows the persistent haze days in the Beijing area, whose percentages have increased gradually with some fluctuations from 1980 to 2015. The number of persistent haze-day amounts to over 70 in 2014 and 2015, which far exceeds the average number of haze days (33) during the investigated period. Moreover, persistent haze days account for more than 70% of the total haze days in 2014 and 2015. In both the urban and rural areas in and around Beijing, the number of persistent haze days has increased by 13 and 8.3 days/decade, respectively; the corresponding percentages of total haze days have also increased by 7 and 8.8% per decade, respectively. In general, we deduce that haze in Beijing will probably become more serious and

FIGURE 3 | Long-term variations in haze days in different seasons and their percentages of annual total haze days (a: Spring; b: Summer; c autumn; d: Winter) from 1980–2015

3.4 | Long-term trends in severe and persistent haze days

Both severe haze days in Beijing and its percentage exhibit positive trends with the rates of 4.1 and 4.3%/decade from 1980 to 2015 (Figure 4a). Recently, continuous haze days occur more frequently, and have gained significant attention among citizens. For instance, haze in the Beijing–Tianjin–Hebei region continued for about 1 week in January 2013, representing one of the severest air-pollution events in the recent 5 years. Figure 4b shows the persistent haze days in the Beijing area, whose percentages have increased gradually with some fluctuations from 1980 to 2015. The number of persistent haze-day amounts to over 70 in 2014 and 2015, which far exceeds the average number of haze days (33) during the investigated period. Moreover, persistent haze days account for more than 70% of the total haze days in 2014 and 2015. In both the urban and rural areas in and around Beijing, the number of persistent haze days has increased by 13 and 8.3 days/decade, respectively; the corresponding percentages of total haze days have also increased by 7 and 8.8% per decade, respectively. In general, we deduce that haze in Beijing will probably become more serious and
longer duration during 1980–2015, the reason of which will be discussed in Section 3.5.

### 3.5 | Impacts of meteorological conditions on haze days in Beijing

In addition to pollutant emissions (Zhang et al., 2009, 2012; Guo et al., 2011, 2016), meteorological conditions also play an important role in air quality, especially when the emission rate is steady. On one hand, many previous studies have reported that variations in large-scale atmospheric circulation can significantly influence the air pollution in China via directly affecting the pressure distribution, precipitation, humidity, and flow field near the surface, which in turn affect the advection of air pollutants, such as that associated with the weakened EAWM and its inter-annual variation (e.g., Chen and Wang, 2015; Li et al., 2016; Zhang et al., 2016; Cai et al., 2017; Pei et al., 2018; Yang et al., 2018). However, the correlation coefficient between haze days at Station 54511 and the EAT index is 0.19, showing a positive correlation, which does not correspond with the actual situation. Therefore, it is unreasonable to apply the uncorrected data at 54511 to characterize the long-term variation in haze days in urban areas of Beijing.

Local meteorological parameters, such as the relative humidity, visibility, wind speed, and precipitation, modulate the formation of polluted haze episodes (Wang and He, 2012; Ding and Liu, 2013; Zheng et al., 2015; Wang and Chen, 2016; Liang et al., 2017; Miao et al., 2017). Figure 5b shows that the visibility in Beijing has been declining, with a decrease of 1.1 km/decade in terms of the daily-averaged visibility. In the recent decade (2006–2015), the average visibility was ≈6.8 km, which is significantly lower than that in the 1980s (≈9.6 km), indicating that there has been a continuous worsening of haze pollution recently. The relative humidity has also trended downward on the whole, dropping during haze days by 1.4%/decade, indicating the development of dry-haze days (Figure 5c). Moreover, the wind speed has decreased gradually at a rate of 0.15 m/s per decade. Days of strong wind speed (daily maximum wind speed ≥8 m/s) have also reduced at a rate of ≈6.8 days/decade, while weak wind-speed days (daily maximum wind speed ≤4 m/s) have increased at a rate of ≈24.5 days/decade (Figure 5d). Haze days present a significant negative correlation with strong wind-speed days (correlation coefficient: $r = -0.52$, $p < 0.01$), but a positive correlation with weak wind-speed days ($r = 0.3$, $p < 0.1$). In addition, there is a significant negative correlation between haze days and rain days ($r = -0.44$, $p < 0.01$, figure not shown). Hence, haze days in Beijing are becoming more severe and drier. In recent years, generally, the reduction in days of local strong wind speed and of rain, as well as the increase in days of weak wind speed, have directly contributed to the weakening of the diffusion capacity of pollutants, which are conducive to haze maintenance, prolonging the duration of haze-pollution days in Beijing.

### 4 | CONCLUSIONS AND DISCUSSIONS

Haze pollution has occurred more frequently in recent years in the Beijing area, which has thus attracted greater attention from the government and wider society. Observations from station 54511 are generally used to study this phenomenon in the Beijing area. This study has confirmed that the time series of haze days from station 54511 are not suitable for the investigation of the inter-annual variability and the long-term trends in haze pollution in Beijing. Instead, time series...
of average haze days from five stations in the Beijing area are selected for the exploration of the long-term variations in haze days in a recent 36-year period encompassing different seasons. The conclusions are summarized as below:

First, comparing haze days derived from station 54,511 with other stations in the vicinity verifies that the station 54,511 is not suitable to represent the haze in the urban area of Beijing, as the haze days derived from its record show the opposite trend to that from other stations.

Secondly, haze days in the urban area have occurred more frequently than those in the rural areas, increasing by 15.8 days/decade, compared with the 11.9 days/decade in rural areas. Haze days have a positive trend during the period of 1980 to 2015, with haze occurring more often in autumn and winter than in spring and summer. In summer, haze days have been increasing faster than the other three seasons. Moreover, severe and persistent haze days respectively have been increasing by 4.1 and 13 days/decade, corresponding to a positive 4.3 and 7%/decade based on the total number of haze days.

Finally, the correlation coefficient between the number haze days in Beijing’s urban areas and the EAT index is −0.6. Since the EAWM has been weakening with a shallow East Asian trough, which causes lesser cold activities, a sinking air motion in the middle-lower troposphere and more stagnantly synoptic circulations in planetary boundary layer, and these conditions are not conducive to the dispersion of pollutants. However, the correlation coefficient between haze days at station 54,511 and the EAT index is 0.19, which is a positive correlation, and which contradicts the known situation. For this reason, it is unreasonable to apply the uncorrected data at station 54,511 to characterize the variation in haze days in Beijing. In addition, hazes in Beijing are becoming more severe and drier. Within the investigated period, the reduction in days of locally strong wind speeds and rain, and the increase in days of weak wind speeds have directly contributed to the weakening of the diffusion of pollutants, prolonging the duration of haze events in Beijing.

However, there are many factors that influence the continuity, representativeness and accuracy of the observation results, such as multiple station relocations, as well as changes in observational methods (Li et al., 2009; Yan et al., 2010). As a result, station 54,511 does not objectively reflect the variation in haze days in the urban areas of Beijing. In contrast, the averaged results from the five selected urban stations in the present investigation are more realistic as representative sites for studying haze days in the urban areas of Beijing during the investigated period, while also

FIGURE 5  Inter-annual variations and trends of (a) EAT index with haze days at the 54,511 and selected five urban stations, (b) annual average visibility and average visibility in haze days, (c) total mixed days of fog and haze, annual average relative humidity, and average relative humidity in haze day, (d) annual average wind speed, and average wind speed in haze day, total days of strong (daily maximum wind speed ≥ 8 m/s) and low wind speed (daily maximum wind speed ≤ 4 m/s) day
demonstrating some new phenomena. For instance, the growth rate of haze days in the summer is most noticeable among the four seasons, with severe and persistent haze days showing significant positive trends. Although the government has adopted a series of policies to reduce emissions in recent years, due to the unfavorable meteorological conditions (Ji et al., 2012; Cai et al., 2017; Ding et al., 2017; Guo et al., 2017; Wu et al., 2017; Pei et al., 2018; Yang et al., 2018), the deterioration of the atmospheric conditions will still be a continuing problem in the urban areas of Beijing.

ACKNOWLEDGEMENTS

This study is supported by the National Key Research and Development Program of China (2016YFC0203300 and 2017YFC1502104), National Natural Science Foundation of China (41575010, 41575003, 41601550, 41505004, and 41675009), and Beijing Natural Science Foundation of China (8171002).

REFERENCES

Cai, W., Li, K., Liao, H., Wang, H.J. and Wu, L.X. (2017) Weather conditions conducive to Beijing severe haze more frequent under climate change. Nature Climate Change, 7(4), 257–262.

Che, H.Z., Zhang, X.Y. and Li, Y. (2009) Haze trends over the capital cities of 31 provinces in China, 1981–2005. Theoretical and Applied Climatology, 97(3), 235–242.

Chen, H.P. and Wang, H.J. (2015) Haze Days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. Journal of Geophysical Research-Atmosphere, 120(12), 5895–5909. https://doi.org/10.1002/2015JD023225.

Ding, Y.H. and Liu, Y.J. (2013) Spatial-temporal variations of fog and haze in China in recent 50 years and their relations with atmospheric humidity. Science China: Earth Sciences, 57(1), 36–46.

Ding, Y.H., Wu, P., Liu, Y.J. and Song, Y.F. (2017) Environmental and dynamic conditions for the occurrence of persistent haze events in North China. Engineering, 3(2), 266–271.

Doyle, M. and Dorling, S.R. (2002) Visibility trends in the UK1950–1997. Atmospheric Environment, 36, 3161–3172.

Gu, Y., Welt, T.W., Law, S.C.K., Dong, G.H., Ho, K.F., Yang, Y. and Yin, S.H.L. (2018) Impacts of sectoral emissions in China and the implications: air quality, public health, crop production, and economic costs. Environmental Research Letters, 13(8). https://doi.org/10.1088/1748-9326/aad138.

Guo, J.P., Zhang, X.Y., Wu, Y.R., Zhaxi, Y.Z., Che, H.Z., Li, B., Wang, W. and Li, X.W. (2011) Spatio-temporal variation trends of satellite-based aerosol optical depth in China during 1980–2008. Atmospheric Environment, 45(37), 6802–6811.

Guo, J.P., He, J., Liu, H.L., Miao, Y.C., Liu, H. and Zhai, P.M. (2016) Impact of various emission control schemes on air quality using WRF-Chem during APEC China 2014. Atmospheric Environment, 140, 311–319.

Guo, C.W., Sun, Z.B., Li, Z.M., Zhang, X.L. and Yang, H.L. (2017) Change of atmospheric pollution diffusion conditions in Beijing in recent 35 years. Environmental Science (in Chinese), 6, 2202–2210.

Hu, Y.D. and Zhou, Z.J. (2009) Temporal and spatial distribution of haze in China. Meteorological Monthly, (in Chinese), 35(7), 73–78.

Hu, K., Yuming, G., Deyun, H., Rongguang, D., Xuchao, Y., Jieming, Z., Fangrong, F., Feng, C., Gongbo, C., Qi, Z., Yunquan, Z., Shanshan, L., Qian, C., Tingting, Y. and Jiaguo, Q. (2018) Mortality burden attributable to PM1 in Zhejiang province, China. Environmental International, 121, 515–522.

Huang, J., Wang, T. and Wang, W. (2014) Climate effects of dust aerosols over East Asian arid and semiarid regions. Journal of Geophysical Research, 119(19), 11398–11416.

Ji, D.S., Wang, Y.S., Wang, L.L., Chen, L.F., Hu, B., Tang, G.Q., Xin, J.Y., Song, T., Wen, T.X. and Sun, Y. (2012) Analysis of heavy pollution episodes in selected cities of northern China. Atmospheric Environment, 50, 338–348.

Jiang, J., Zhou, W., Cheng, Z., Wang, S.X., He, K.B. and Hao, J.M. (2015) Particulate matter distributions in China during a winter period with frequent pollution episodes. Aerosol and Air Quality Research, 15(2), 494–503.

Lee, D. (1990) The influence of wind direction, circulation type and air pollution emissions on summer visibility trends in southern England. Atmospheric Environment, 24A, 195–201.

Li, Z. and Yan, Z.W. (2009) Homogenized daily mean/maximum/minimum temperature series for China from 1960–2008. Atmospheric and Oceanic Science Letters, 2(4), 1–7.

Li, Q.X., Zhang, H.Z., Chen, J., Li, X.N. and Jones, P.I.L. (2009) A mainland China homogenized historical temperature dataset of 1951–2004. Bulletin of the American Meteorological Society, 90, 1062–1065.

Li, Z., Lau, W.K.M., Ramanathan, V., Wu, G., Ding, Y., Mannoj, M.G., Liu, J., Qian, Y., Li, J., Zhou, T., Fan, J., Rosenfeld, D., Ming, Y., Wang, Y., Huang, J., Wang, B., Xu, X., Lee, S.S., Cribb, M., Zhang, F., Yang, X., Zhao, C., Takeda, W., Wang, K., Xia, X., Yin, Y., Zhang, H., Guo, J., Zhai, P.M., Sugimoto, N., Babu, S.S. and Brasseur, G.P. (2016) Aerosol and monsoon climate interactions over Asia. Reviews of Geophysics, 54(4), 866–929. https://doi.org/10.1002/2015RG000500.

Liang, P.F., Zhu, T., Fang, Y.H., Li, Y.G., Han, Y.Q., Wu, Y.S., Hu, M. and Wang, J.X. (2017) The role of meteorological conditions and pollution control strategies in reducing air pollution in Beijing during APEC 2014 and victory parade 2015. Atmospheric Chemistry and Physics, 17(22), 13921–13940.

Liu, X.G., Li, J., Qu, Y., Han, T., Hou, L., Gu, J., Chen, C., Yang, Y., Liu, X. and Yang, T. (2013) Formation and evolution mechanism of regional haze: a case study in the megacity Beijing. China. Atmospheric Chemistry and Physics, 13, 4501–4514.

Liu, Z.R., Hu, B., Liu, Q., Sun, Y. and Wang, Y.S. (2014) Source apportionment of urban fine particle number concentration during summertime in Beijing. Atmospheric Environment, 96, 359–369.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Hau, H. and He, K.B. (2015) High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. Atmospheric Chemistry & Physics, 15(13), 18877–18837.

Miao, Y.C., Liu, S.H., Zheng, Y.J., Wang, S., Chen, B.C., Zheng, H. and Zhao, J.C. (2015a) Numerical study of the effects of local atmospheric circulations on a pollution event over Beijing–Tianjin–Hebei, China. Journal of Environmental Sciences, 30, 9–20.

Miao, Y.C., Hu, X.M., Liu, S.H., Qian, T.T., Xue, M., Zheng, Y.J. and Wang, S. (2015b) Seasonal variation of local atmospheric circulations and boundary layer structure in the Beijing-Tianjin-Hebei region and implications for air quality. Journal of Advances in Modeling Earth Systems, 7, 1–25.

Miao, Y., Guo, J., Liu, S., Liu, H., Li, Z., Zhang, W. and Zhai, P. (2017) Classification of summertime synoptic patterns in Beijing and their associations with boundary layer structure affecting aerosol pollution. Atmospheric Chemistry & Physics, 17, 1–33.

Pei, L., Yan, Z.W., Sun, Z.B., Miao, S.G. and Yao, Y. (2018) Increasing persistent haze in Beijing: potential impacts of weakening East Asian winter monsoons associated with northwestern Pacific sea surface temperature trends. Atmospheric Chemistry and Physics, 18, 3173–3183.

Ren, G., Zhou, Y., Chu, Z., Zhou, J.X., Zhang, A.Y., Guo, J. and Liu, X.F. (2008) Urbanization effect on observed surface air temperature trend in North China. Journal of Climate, 21(6), 1333–1348.

Schichtel, B.A., Husar, R.B., Falke, S.R. and Wilson, W.E. (2001) Haze trends over the united states, 1980–1995. Atmospheric Environment, 35(30), 5205–5210.

Song, L.C., Gao, R., Li, Y. and Wang, G.F. (2013) Analysis of China's haze days in winter half year and climatic background during 1961–2012. Progressus Inquisitionis DE Mutazione Climatis, (in Chinese), 9(5), 313–318.
