Climate variability or anthropogenic emissions: which caused Beijing Haze?

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Abstract

Beijing Haze has been phenomenal, especially for winter, and widely considered a result of the increasing anthropogenic emissions of atmospheric pollutants in the region. Since 2013, the pollutant emissions have been reduced with the help of a series of emission-control actions. However, severe haze events still occurred frequently in Beijing in recent winters, e.g., those of 2015 and 2016, implying that other factors such as meteorological conditions and interannual climate variability have also played an important role in forming the haze. Based on homogenized station observations, atmospheric circulation reanalysis and anthropogenic emissions data for the period 1980–2017, this paper attempts to quantify the relative importance of anthropogenic emissions and climatic conditions to the frequency and intensity of Beijing Haze in winter. It is found that the frequency (number) of hazy days exhibits large interannual variability and little trend, and its variations were mainly controlled by climate variability, with a correlation coefficient of 0.77. On the other hand, the intensity of haze displays strong interannual variability and a significant increasing trend during 1980–2012 and a notable decreasing trend during 2012–2017. The multiple linear regression model suggests that about half of the total variance of the haze intensity is explained by climate variability (mainly for interannual variations), and another half by the changing emissions (mainly for the trends).

1. Introduction

Air pollution in China has been a serious environmental problem affecting the daily life of more than two-thirds of its population (Liu and Diamond 2005, Zhang 2017). The capital city Beijing and its surrounding areas, as one of the most populated and polluted regions, has frequently been shrouded by severe haze episodes, especially during winter (Ding and Liu 2014, Huang et al 2014). Severe haze with considerably high levels of PM$_{2.5}$ not only deteriorates the ambient visibility, endangering ground and air traffic and consequently influencing economic activities (Li et al 2016), but also detrimentally affects human health, inducing respiratory illness, heart disease, premature death and cancer (Silva et al 2013, Zhang et al 2017). Haze is essentially caused by fine particulates from natural and anthropogenic emission sources under specific meteorological conditions (Wang et al 2014). Increasingly, anthropogenic emissions of pollutants into the atmosphere because of rapid economic development and urbanization are considered as the major cause of increasingly frequent hazes in China during the past decades. Confronted with such an increasingly influential problem, the Chinese State Council implemented the ‘Atmospheric Pollution Prevention and Control Action Plan’ (Clean Air Action) with US $277 billion investments in 2013. Since then, the emissions have remarkably decreased by 59% for SO$_2$, 21% for NO$_x$, 23% for CO, 36% for PM$_{10}$, 33% for PM$_{2.5}$, 28% for BC, and 32% for OC (Zheng et al 2018). However, severe haze episodes still occasionally prevailed...
in the Beijing-Tianjin-Hebei (BTH) region in recent years. A case study comparing two extreme years between 2017 (best, clear winter) and 2016 (worst, hazy winter) emphasized the critical importance of the large-scale atmospheric circulation anomalies (Yan et al. 2018). Therefore, it is beneficial to assess the influence of climatic variability on haze.

Meteorological conditions are essential for formation and development of haze (Zhang et al. 2014, Wu et al. 2017, An et al. 2019). Local meteorological conditions during winter haze episodes in Beijing are usually stagnant, accompanied by abundant moisture, weak surface winds and an inversion in the boundary layer (Wang et al. 2015, Wu et al. 2017). These weather conditions are largely affected by large-scale atmospheric circulation anomalies with strong interannual variability, such as the East Asian Winter Monsoon (EAWM), Arctic sea ice and sea surface temperature anomalies in the northwestern Pacific (Wang et al. 2015, Wu et al. 2016, Pei et al. 2018). Although both meteorological conditions and anthropogenic emissions have been identified as important factors for Beijing Haze, their relative contributions to the haze in a long-time perspective remain controversial.

A recent study noted that the number of winter haze days in most of eastern China during 1973–2012 was mainly controlled by meteorological and climate variations and did not exhibit any significant increasing trend despite the 2.5-fold increase in the anthropogenic emissions of particulate matter and its precursors (PM emissions) in the same period (Mao et al. 2019). In contrast, an assessment of the reduction in PM$_{2.5}$ concentrations in China during 2013–2017 suggested that the Clean Air Action was the dominant factor for improvement in air quality in recent years (Vu et al. 2019, Zhai et al. 2019). This discrepancy was partly caused by the different indices and definitions of haze used in the studies. In meteorology, researchers examined historical changes of haze days, which is usually defined based on the observations of relative humidity and visibility with specified criteria, such as daily mean visibility <10 km and relative humidity <90%, with a haze weather phenomenon (Ding and Liu 2014). While, in environmental science, researchers apply annual mean or seasonal mean concentrations of PM$_{2.5}$ to represent intensity of haze (e.g. Zhang et al. 2013, Zhang et al. 2019). Therefore, it is beneficial to separate the frequency and intensity of haze for exploring the relative influence of climatic variability and anthropogenic emissions.

In this study, we propose a new perspective on understanding how climate variability and anthropogenic emissions influenced Beijing Haze during 1980–2017, focusing on two aspects of winter hazes in Beijing: the frequency (the number of haze days) and intensity (the mean visibility during haze episodes). Firstly, based on updated homogenized station data, we examine the characteristics of frequency and intensity of winter haze in Beijing for the past decades. Then based on atmospheric reanalysis data, local meteorological variables and anthropogenic emissions data, applied Multiple Linear Regression (MLR) model, we assess relative contributions of meteorological variables and anthropogenic emissions on the variations and changes in frequency/intensity of winter haze, respectively. The data and methods used are explained in section 2, while the results are presented in section 3. Finally the conclusions of the study, along with some discussions, are summarized in section 4.

2. Data and methods

2.1. Definitions of haze indices used

Meteorological data used here to define a haze day were obtained from homogenized station observations collected by the National Meteorological Information Center of China (http://data.cma.cn/), including relative humidity, visibility and weather phenomenon records. Consecutive records during winter (December, January and February; DJF) from 1980 to 2018 at 20 stations in the Beijing region are used. Pei et al. (2018) adjusted visibility data to maintain their consistency before analysis, i.e. the visibility observations since 2013 were transformed to be comparable to the early man-made observations. In this study, a haze day at each station is defined if a haze weather phenomenon is recorded with daily mean visibility <10 km and daily mean relative humidity <90%, and excludes sand, dust, snow and other weather phenomena influencing visibility. A haze day in the Beijing region is defined if there is at least one (threshold number of N = 1) station with haze on the day (Pei et al. 2018). We calculated the correlation between the series of haze days defined with N = 1 and 2, and that with climatic variables, anthropogenic emissions and the associated MLR results, as shown in table S1, available online at stacks.iop.org/ERL/15/034004/mmedia. The results indicate that the different series of haze days (defined with N = 1 and 2) have similar interannual variability, although the increasing trend of the haze day series for N = 1 is relatively minor. The correlation coefficients between the (detrended) series of haze days (N = 1 and 2) and meteorological variables for the period 1980–2017 are all significant at the $\alpha = 0.01$ level. When meteorological conditions and total amount of anthropogenic emissions are considered in the MLR model, the variance explained about the N = 2 series does not show notable differences with those about the N = 1 series. Therefore, using a different threshold number (N) of stations to define a haze day in Beijing has little influence on the conclusions of this paper. The intensity of a haze day here is measured by average visibility over the Beijing region when haze occurs. The climatological mean of the average visibility over the Beijing region during winter is around 20 km; and the average visibility during the haze days is much
smaller than 20 km. To ensure a meaningful positive intensity value, we define the intensity of haze as _μ_, the average visibility over the Beijing region (20 sites) when haze occurred (unit: km). The frequency of haze is the number of the haze days during a period (a month or a winter).

### 2.2. Climatic conditions

Climatic conditions corresponding to Beijing haze in winter include local meteorological factors and the associated large-scale atmospheric circulation factors. Homogenized station data are used to depict local meteorological conditions over the Beijing region, including relative humidity and surface wind speeds, collected from the National Meteorological Information Center of China (http://data.cma.cn/) for the period 1980–2018. Monthly atmospheric analysis, including meridional and zonal wind speeds, sea level pressure (SLP) and air temperature, used for depicting large-scale atmospheric features for winter hazes in Beijing, are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) for the period 1980–2018, of 2.5° resolution (Kalnay et al. 1997).

### 2.3. Anthropogenic emissions

To obtain long-term changes in anthropogenic emissions in China, two datasets of the emissions of particulate matter and its precursors are used: the Emission Database for Global Atmospheric Research (EDGAR, http://edgar.jrc.ec.europa.eu/) and the Multi-resolution Emission Inventory for China (MEIC, http://www.meicmodel.org). Eight chemical species, including both gaseous and aerosol species, are used in calculating the total amounts of anthropogenic emissions: sulfur dioxide (SO_2), nitrogen oxides (NO_x), nonmethane volatile organic compounds (NMVOCs), ammonia (NH_3), particulate matter with diameter less than or equal to 10 μm (PM_{10}), particulate matter with diameter less than or equal to 2.5 μm (PM_{2.5}), black carbon (BC) and organic carbon (OC). OC, BC, PM_{2.5} and PM_{10} are the primary Particulate Matter (PM) emissions from industry and other sources (Zhang et al. 2013, Hu et al. 2015). SO_2, NH_3 and NO_x are the emissions of gas precursors for secondary inorganic aerosols (SIA) and NMVOCs for the secondary organic aerosols (SOA) (An et al. 2019). During wintertime heating period in Beijing, in addition to primary PM, the contribution of SOA and SIA are found to be the most important to the chemical composition and sources of PM_{2.5} when severe haze episodes occurred (Huang et al. 2014, Wang et al. 2016).

During severe haze episodes in Beijing, the regional transport of pollutants from cities southeast of Beijing, including Tianjin and Hebei province (BTH), play an important role (Zheng et al. 2015). Therefore, chemical species over the BTH region (36°–42°N, 114°–119°E, figure 1(a)) are necessary for calculating anthropogenic emissions influential to Beijing Haze. The time series of total amounts of anthropogenic emissions and each chemical species over the BTH region based on the EDGAR and MEIC during the period 1980–2011 and 2010–2017 are shown in figures 1(b) and (c), respectively. Reconstruction of the normalized time series of each species (colors) and total amounts of anthropogenic emissions (black) in BTH for the period 1980–2017 are shown in figure 1(d), consisting of the normalized time series from EDGAR for the period 1980–2011 and that from MEIC for the period 2012–2017. Statistical analyses indicate that all species, except for OC, exhibit significant positive trends for the period 1980–2011 (table S2). However, for the period from 2010 to 2017, particularly since 2012, most of the species decreased markedly, except for NMVOCs, as a consequence of active clean air policies implemented in recent years (Zheng et al. 2018). Time series of total amounts of anthropogenic emissions indicated a significantly increasing period in 1980–2012 and a notable decreasing period in 2012–2017. More than 80% of the total variance of the time series can explained by the trends.

### 2.4. Multiple linear regression (MLR) model

In this paper, the MLR model was applied to link the observed haze frequency and intensity (predictant) in Beijing and meteorological/climatic indices and anthropogenic emissions (predictors). Through correlation analysis, several factors are selected to reproduce the observed haze frequency and intensity. The equations of the MLR models are listed in table 1.

### 3. Results

#### 3.1. Frequency and intensity of winter haze in Beijing during 1980–2017

Based on homogenized observational data in Beijing for the period 1980–2017, we found that the frequency of winter haze exhibits strong interannual variability without any significant trend (black curve in figure 2(a)), consistent with previous studies (Chen and Wang 2015, Mao et al. 2019). However, the time series of haze intensity exhibits a significant positive trend from 1980 to 2012, reaches a peak in 2012 and then notably decreases to a lower point in 2017 (black curve in figure 2(b)). During the two periods, more than 50% of the total variance of the intensity series can be explained by the trends. From 1980 to 2012, the average visibility during haze days decreased by 24%, suggesting intensifying winter haze during this period. The most polluted winter was 2012 (2012/Dec–2013/Jan), with an average visibility of 10.6 km when haze occurred. As pointed out in many studies, serious haze episodes repeatedly occurred in northern China during January 2013, which is the most severe haze pollution events in the observational history (Huang...
After this year, the haze intensity turns to an unprecedented negative trend, with the average visibility of haze episodes increasing by 34%. The haze intensity for the winter of 2017 (Dec 2017 to Feb 2018) was 4.5, with an average visibility of 15.5 km, which was the highest value in the past 20 years.

3.2. The number of winter haze days is controlled by climatic conditions

Local meteorological conditions over the Beijing region play important roles in the formation and development of haze episodes, such as weak surface wind speeds, high relative humidity, and inversion in the boundary layer (Wu et al. 2017). Through statistical analysis, we found that surface wind speeds (Ws) and relative humidity (RH) over the Beijing region are significantly correlated with the number of winter haze days during 1980–2017, with correlation coefficients of -0.54 and 0.64, respectively, both significant at the α = 0.01 level (table 1). It is consistent with former studies that surface wind speeds are generally very low (only 1–2 ms⁻¹) when winter hazes frequently occur in the BTH, unfavorable for the dispersion of air pollutants and conducive to the accumulation of pollutants (Wu et al. 2017). The regional mean winter wind speed series in Beijing indicates a significant negative trend during 1961–2008, as a result of both urbanization and large-scale climate change in the region (Li et al. 2011, Zhang et al. 2018). Abundant moisture over the Beijing region creates favorable humidity conditions for Beijing hazes, linked to the hygroscopicity and scatter of particles (Wang et al. 2014) and the efficiencies of secondary pollutants formation (Wang et al. 2016), leading to lower visibility (Wu et al. 2017). We also examined a suite of other local meteorological variables, such as near-surface air temperature, but its regional averages are not as highly correlated with the haze frequency.

As proposed by Pei and Yan (2018), four large-scale factors are selected to depict large-scale atmospheric conditions associated with the frequency of Beijing hazes in winter, which are the Siberian High Intensity (SHI), the meridional wind speeds anomaly at 850 hPa over northern China (V850), the difference in zonal wind speeds at 500 hPa (U500), and the vertical difference in air temperature (ΔT), respectively.

**Figure 1.** (a) The Beijing-Tianjin-Hebei region (36–42 °N, 114–119 °E) (BTH) used to calculate the changes in anthropogenic emissions. (b) Temporal variations in emissions of major air pollutants in the BTH during 1980–2011 based on the EDGAR dataset. Dashed lines are linear regressions (with corresponding equations). (c) Same as (b) but for the period 2010–2017 based on the MEIC dataset in China. (d) Reconstruction of the normalized series of each species (colors) and total amounts (black) of anthropogenic emissions during 1980–2017.
Table 1. Correlation coefficients between the frequency/intensity and climatic conditions and anthropogenic emissions and the associated regression results based on the multiple linear regression (MLR) model for the period 1980–2017.

| Correlation coefficients (R) | Climatic conditions | Large-scale climatic factors | Anthropogenic emissions | Multiple Linear Regression |
|------------------------------|---------------------|-----------------------------|-------------------------|----------------------------|
|                              | Local meteorological variables | Large-scale climatic factors |                          |                            |
|                              | Relative humidity (RH) | Surface wind speeds (Ws) | 2 m temperature | SHI | V850 | U500 | ΔT | Local | Large-scale | Climatic | Climatic + Emissions |
| Frequency                    | 0.64                | -0.54                       | 0.31                  | -0.59 | 0.49 | 0.65 | 0.51 | 0.13 | 0.66<sup>a</sup> | 0.71<sup>b</sup> | 0.77<sup>c</sup> | 0.77<sup>d</sup> |
| (Detrended)                  | 0.63                | -0.57                       |                      | -0.64 | 0.48 | 0.66 | 0.50 |      | R<sup>2</sup> = 0.44 | R<sup>2</sup> = 0.30 | R<sup>2</sup> = 0.59 | R<sup>2</sup> = 0.59 |
| Intensity                    | 0.56                | -0.67                       | 0.11                 | 0.05  | 0.53 | 0.20 | 0.32 | 0.74<sup>e</sup> [−0.07, 0.74] | R<sup>2</sup> = 0.55 |                          |            |
| (Detrended)                  | 0.67                | -0.48                       | -0.15                | -0.14 | 0.55 | 0.27 | 0.30 | 0.43 |            |                          |            |            |

Bold: significant correlation coefficients at α = 0.01. Red: the largest correlation coefficient. Emissions of each pollutant are incorporated individually in the MLR models, shown in brackets.

The MLR equations are listed as below:

-<sup>a</sup> y = 0.80RH − 6.9Ws + 17.7
-<sup>b</sup> y = -2.5SHI + 3.07V850 + 1.81U500 − 0.58ΔT + 37.97
-<sup>c</sup> y = -3.12SHI − 0.51V850 + 0.90U500 − 0.36ΔT + 0.63RH − 6.48Ws + 24.45
-<sup>d</sup> y = -3.86SHI − 0.42V850 + 0.47U500 − 0.43ΔT + 0.68RH − 3.60Ws + 0.96Emissions + 15.65
-<sup>e</sup> y = 0.07RH − 3.21Ws + 9.76
-<sup>f</sup> y = 0.84V850 + 5.57
-<sup>g</sup> y = -0.24V850 + 0.09RH − 3.54Ws + 9.34
-<sup>h</sup> y = -0.09V850 + 0.114RH − 0.38Ws + 0.98Emissions + 0.06
Discussed in Pei and Yan (2018). Physical mechanisms about how these large-scale atmospheric circulation anomalies influenced frequency of winter haze days in Beijing are discussed in Pei and Yan (2018). The correlation coefficients between the above four large-scale atmospheric circulation factors and the number of winter haze days in Beijing for the period 1980–2017 are listed in table 1, all significant at the $\alpha = 0.01$ level. However, these four variables are not independent, SHI, V850, U500 and $\Delta T$ are correlated with correlation coefficients over the 1980–2017 period ranging between 0.41 and 0.83. Thus, these favorable large-scale atmospheric circulation factors co-occur to provide a conducive setting to frequent haze events in the wintertime.

The MLR model was applied to link the number of winter haze days in Beijing (predictant) and climatic indices or anthropogenic emissions (predictors). The multiple correlation coefficient is 0.77 (table 1), based on six climatic factors (four large-scale atmospheric circulation indices and two local meteorological indices), significant at the $\alpha = 0.01$ level (red in figure 2(a)). This result suggests that 59.3% of the total variance in the number of winter haze days during 1980–2017 can be explained by climatic variability. When both climatic variability and total amounts of anthropogenic emissions are considered in the MLR model, the variance explained does not increase as well, as shown in table S3. When large-scale atmospheric circulation factors (4 indices) and local meteorological factors (2 indices) are considered in MLR, the correlation coefficients are 0.71 and 0.66 (brown and blue in figure 2(a)), respectively. As the total variance of the frequency of winter haze days in Beijing can be explained by large-scale atmospheric circulation factors only. Therefore, climatic conditions, particularly large-scale atmospheric circulation factors, are dominant in determining the number of haze days in winter, while changes in anthropogenic emissions have little effect. It is consistent with former conclusions about changes in the frequency of haze days in China and the correlated influencing factors (e.g. Wang et al 2015, Zhang et al 2015, Mao et al 2019).

3.3 Both anthropogenic emissions and climatic conditions determined the changes in haze intensity

Based on statistical analysis, it is found that surface wind speeds and relative humidity are highly correlated with the haze intensity, with correlation coefficients of $-0.67$ and 0.56, respectively, both significant at $\alpha = 0.01$ (table 1). The anomalous southerly flows give rise to the accumulation of pollutants and moisture over Beijing, with reduced surface wind speeds, which is conducive to the accumulation of air pollutants (Wu et al 2017). Abundant moisture over the Beijing region enhances aerosol scattering and

**Figure 2.** (a) Time series of the observed haze frequency (black), the reconstructed haze frequency via MLR models (brown for large-scale variables; blue for local meteorological variables; red for large + local scale variables) for the period 1980–2017. Black dashed line denotes linear regression of the observed haze frequency series, and equations are statistics for the regression. (b) Time series of the observed haze intensity (black), reconstructed haze intensity from the applied MLR models (red for climatic variability; pink for climatic variability plus emissions) and anthropogenic emissions (green) for the period 1980–2017. Correlation coefficients between various factors and the observed haze frequency/intensity series are in parentheses.
secondary aerosol formation, resulting in the accumulation of pollutants (Wu et al 2019, An et al 2019).

Figure S2 depicts correlation coefficients between anomalous variables of atmospheric circulation from the near-surface to the upper troposphere and the intensity of haze days in Beijing in winter from 1980 to 2017. Only one large-scale factor, that is V850, is highly correlated with the changes in haze intensity in Beijing, with a correlation coefficient of 0.53, significant at \( \alpha = 0.01 \) (table 1). Anomalous southerlies imply weakening of the northerly winds or even a reversal to southerly flow in the region (figure S2(b)), which is favorable for the transport of warm, moist air and pollutants to the Beijing region. Abundant and warm moisture is necessary for the formation and maintenance of haze episodes because it is favorable for efficient secondary inorganic aerosol transformation and hygroscopic growth of haze particles (Wang et al 2016). Meanwhile, influenced by anomalous southerlies, large amounts of air pollutants are transported to the Beijing region, leading to a significant reduction in visibility (Tang et al 2016).

On one hand, when climatic indices (V850, surface wind speeds and relative humidity) are considered in the MLR model, the multiple correlation coefficient is 0.72 (red in figure 2(b)), statistically significant at the 0.01 level. It suggests that 51.8% of the total variance in haze intensity can be explained by climatic conditions. However, its linear trends during the two periods (1980–2012 and 2012–2017) are weaker than those of the observed haze intensity, indicating that the changes in climatic conditions alone are not enough to explain the observed trends of haze intensity during these periods. On the other hand, changes in total amounts of anthropogenic emissions are highly correlated with haze intensity in Beijing, with a correlation coefficient of 0.74 (green in figure 2(b)), suggesting that changes in anthropogenic emissions can explain 54.8% of the variance of haze intensity in the past decades. When both changes in anthropogenic emissions and climatic conditions are considered in the MLR model, the multiple correlation coefficient is as high as 0.86. Furthermore, the trends of the reconstructed haze intensity are highly consistent with the observed. Correlation coefficients between each species of anthropogenic emissions and time series of haze intensity are shown in table S2, indicating most are highly correlated, except for NH₃ and NMVOCs. Emissions of each pollutant are incorporated individually in the MLR models, suggesting the uncertainties of each species of emissions in MLR results (table S3). Therefore, both changes in emissions and meteorological conditions are responsible for the changes in haze intensity (pink in figure 2(b)), which explain 74% of the total variance of haze intensity for the period 1980–2017. In details, about half of the total variance of the haze intensity can be explained by climate variability (mainly for interannual variations), and about half by the changing emissions (mainly for the trends).

4. Summary and discussions

Due to the challenge of such a serious problem, the Chinese government has successively introduced a five-year plan in 2013 (Clean Air Action) and a three-year plan in 2018 (Defending the Blue Sky) and even made an amendment of the Law on the Prevention and Control of Atmospheric Pollution in 2018. However, serious air pollution still occurred frequently around the Beijing-Tianjin-Hebei region. The large interannual variability of air pollution in recent years was partly caused by natural climate variability (Wang 2018, Yan et al 2018). This paper aims at quantifying the relative influences of anthropogenic emissions and climatic variability on Beijing Haze from a climate perspective. The main conclusions of the present study are as follows.

(1) Based on long-term homogenized observational data for the period 1980–2017, we found that the frequency of winter haze in Beijing exhibits strong interannual variability without significant long-term trend. In contrast, the haze intensity exhibits a notable increasing trend during 1980–2012, with a peak in 2012, and a decreasing trend during 2012–2017, also with strong interannual variability.

(2) Based on observations of meteorological variables, atmospheric reanalysis data and anthropogenic emissions over the BTH region, we found that the frequency of winter haze is mainly controlled by climatic variability, including large-scale atmospheric circulation factors (SHI, V850, U500 and \( \Delta T \)) and local meteorological factors (relative humidity and surface wind speeds), while hardly influenced by the emissions. The number of winter haze days has a significant correlation coefficient (\( R = 0.77 \)) with the MLR reconstructed from climatic variability. Over 50% of the total variance of the frequency can be explained by the selected large-scale atmospheric circulation factors only.

(3) The MLR model suggests that about half of the total variances of the haze intensity can be explained by climate variability (mainly for interannual variations), and about half by the changing emissions (mainly for the trends). Considering both changes in emissions and meteorological conditions in the MLR model, the multiple correlation coefficient is as high as 0.85, indicating 72% of the total variance of haze intensity can be well explained for the period 1980–2017.

Both particulate matters from various sources and specific meteorological conditions are necessary in the formation and development of Beijing Haze, while the associated influences are different. The former, closely linked to anthropogenic emissions, play an important
role in the intensity of Beijing Haze, particularly on trends. The latter, including local meteorological variables and large-scale atmospheric circulation factors, with strong interannual variability, mainly determine the frequency of Beijing Haze. Regional weather conditions in association with severe haze events in Beijing are usually stagnant, accompanied by weakened surface wind speeds, high relative humidity, which were largely modulated by large-scale atmospheric circulations and the underlying climatic factors (Chen and Wang 2015, Wu et al 2017, Pei et al 2018). Besides, increasing evidences indicate that greenhouse effect is expected to increase near surface atmospheric stagnation (Wu et al 2013, Horton et al 2014), contributed to the positive trend in the number of winter haze days in Beijing (Cai et al 2017, Pei and Yan 2018, Li et al 2018, Callahan et al 2019). The present conclusions with above discussions are schematically depicted in figure 3. In fact, haze is a weather phenomenon that occurs occasionally and has been recorded as ‘haze disaster’, ‘wind haze’ and ‘rain haze’ in ancient Chinese literatures. Rapid industrialization and urbanization in China caused increasing amounts of pollutants into the atmosphere, giving rise to haze episodes being more severe with lower visibility. Since 2013, the Chinese government has made great efforts in solving haze issues and has implemented active clean air actions. Since then, even if severe haze episodes still occurred occasionally in North China, the average intensity of haze has remarkably reduced, highlighting the effectiveness of emission-cut measures in recent years.

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Competing financial interests

The authors declare no competing financial interests.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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