Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics Discussions

Increasing persistent hazes in Beijing: potential impacts of weakening East Asian Winter Monsoons associated with northwestern Pacific SST trend since 1900.

Lin Pei[1]*, Zhongwei Yan[2], Zhaobin Sun[1], Shiguang Miao[1], Yao Yao[2]

[1] Institute of Urban Meteorology, China Meteorological Administration, Beijing, China
[2] RCE-TEA, Institute of Atmospheric Physics, University of Chinese Academy of Sciences, Beijing, China
* Corresponding author: lpei@ium.cn

Abstract:

This paper analyzes the variations of persistent haze days in boreal winter in Beijing and demonstrates a significant increasing trend with increasing probability of the persistent haze events (PHEs) during 1980-2016. The atmospheric conditions favorable for the increasing PHEs include reduced surface meridional winds and weakened East Asian Trough in the mid-troposphere. These conditions indicate a weakening East Asian Winter Monsoon (EAWM) system, which is then found to be associated with an anomalous warm and high-pressure system in the mid-lower troposphere over the northwestern Pacific. We proposed a practical circulation indicator using the anomalous southerly winds at 850 hPa over North China. The increasing occurrence of the persistent haze days in Beijing is closely related with increasing frequencies of unusual persistent southerly episodes in recent decades. Over the past centennial period 1900-2009, the anomalous meridional winds at 850 hPa in North China were positively correlated with the sea surface temperature anomalies over the northwestern Pacific. Based on the present results, we outline an observation-based mechanism highlighting the role of large-scale climate warming on the increasing trend of PHEs in Beijing.

1 Introduction

In the past decades, pollutant emissions have considerably increased in China due to the rapid economic development (Guo et al., 2011; Zhou et al., 2010). The capital city Beijing has consequently encountered with an increasing frequency of severe hazes especially in the winter (Niu et al., 2010; Ding and Liu, 2014; Chen and Wang, 2015; Wang et al., 2015). Notable is the increasing tendency of persistence haze events (PHEs) during the past decades (Zhang et al., 2015; Wu et al., 2017). Severe haze with a high concentration of fine particles such as PM2.5 not only leads to a sharp decrease in visibility causing traffic hazards and disruptions and hence affecting economic activities (Chen and Wang, 2015; Li et al.,2016; Huang et al., 2014), but also induces serious health problems dealing with respiratory illnesses, heart disease, premature death and cancers (Pope and Dockery, 2006; Wang and Mauzerall, 2006; Hou et al., 2012; Sun et al., 2013; Xie et al., 2014; Gao et al., 2015). PHEs would aggravate these serious consequences. During 14-25 January 2013, eastern China was hit by a persistent severe haze event affecting about 800 million people, while Beijing reached its highest level of air pollution in record and announced the first orange haze alert (Ding and Liu, 2014; Zhang et al., 2014). In this period, about 200 cases of premature death and thousands of cases of hospital admissions for respiratory, cardiovascular and asthma bronchitis diseases were found to be associated with the high level of PM 2.5 (Xu et al., 2013). Correspondingly, this event caused about 489 million RMB health-related economic losses. Thus, detailed studies on the characteristics and underlying reasons of the increasing PHEs around Beijing are urgently needed.

Many studies suggested that the increased emissions of pollutants into the atmosphere due to rapid economic development and urbanization in China were the main cause of the increasing haze days (Liu and Diamond, 2005; Wang et al., 2013; Wang et al., 2014). Zhang et al. (2013) suggest that chemical constituents and sources of PM2.5 in Beijing can largely vary with seasons, which are characterized by variable meteorology and diverse air pollution sources. For pollutions in Beijing, vehicles, coal combustion and cross-regional transfers are the identical sources of PM2.5 (He et al., 2013). Nevertheless, specific meteorological conditions play a key role in forming a haze weather phenomenon (Chen and Wang, 2015; Li and Zhang, 2016; Huang et al., 2014; Tang et al., 2015a). The severe haze event in January 2013 in eastern China was closely related to the persistent weak surface winds and the atmospheric boundary layer inversion near the surface (Zhang et al., 2014). By analyzing the haze episode during 21-26 October 2014, Zhu et al. (2016) found that the severe air pollution in Beijing was formed mainly by the southerly transport and strengthened by local contributions. The main meteorological conditions during PHEs around Beijing include inversion in the atmospheric boundary layer, weak winds near the surface and sufficient moisture in the air (Liao et al., 2014). Wu et al. (2017) categorized two types of circulation conditions during PHEs in Beijing–Tianjin–Hebei region: the zonal westerly type and the high-pressure ridge type, giving rise to the descending air motion in the mid-lower troposphere, thus leading to a lower boundary layer with higher concentration of pollutants. These studies have explored ambient conditions in case studies. However, it remained unclear about the large-scale atmospheric circulation backgrounds of PHEs around Beijing from a perspective of climate change.

Recently, the role of underlying climatic factors in modulating regional weather conditions in association with severe haze events has been reported (e.g., Niu et al., 2010; Wang et al., 2015; Cai et al., 2017; Zou et al., 2017). These climatic factors, including the weakening East Asian Winter Monsoon (EAWM) and related decreasing wind speeds (Niu et al., 2010), the increasing relative humidity in the region (Chen and Wang, 2015), the reducing Arctic Sea ice (Wang et al., 2015) and the anomalous SST in the subtropical western Pacific (Yin and Wang, 2016), etc., should have influenced the changes of severe hazes. The observed weakening trend of the EAWM during the past few decades caused significant weakening winds over North China, subdued the atmospheric transport of pollutants, and hence contributed to the increasing number of haze days (Niu et al., 2010; Huang et al., 2012; Li et al., 2016). The latest studies analyzed possible influence of anthropogenic climate change on haze occurrences. Based on historical and future climate simulations, Cai et al. (2017) suggested that the anthropogenic greenhouse gas emissions and the associated changes of the atmospheric circulation might favor the haze weather conditions in Beijing. Zou et al. (2017) indicated that the extremely poor ventilation conditions in eastern China could be linked to the Arctic sea ice loss and the extensive Eurasia snowfall, which led to the unprecedented severe haze event in January 2013. However, the linkage of underlying climatic factors to the changes in PHEs around Beijing was still unclear, especially on long-term (multidecadal to centennial) timescales. Specifically, it is interesting to explore how large-scale climatic warming contributed to the increasing trend of PHEs in Beijing in the last decades.

In this paper, we analyze the characteristics of the PHEs in Beijing based on updated observations, the associated atmospheric circulation changes related to the EAWM system during 1980-2016. Furthermore, we explore the possible link between anomalous meridional winds at 850 hPa in North China, as a practical index of EASM, and the SSTA over the northwestern Pacific over the past centennial period 1900-2009. The data and methods used are described in Sect. 2. In Sect. 3, we demonstrate the change of the PHEs in Beijing in the past decades, the associated changes of meteorological conditions of the EAWM system and investigate the linkage between anomalous meriodional winds and SSTA in the northwestern (NW) Pacific since 1900. Conclusions with more discussions are in Sect. 4.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics Discussions

2 Data and methods

2.1 Local visibility observations

The meteorological data used in this study are from the quality-controlled station observations collected at the National Meteorological Information Center of China, including the relative humidity, visibility, and weather phenomena. The data include 4 observations per day at 02:00, 08:00, 14:00, and 20:00 local time (LT). Consecutive records during the winters (December, January and February, DJF) from 1980 to 2016 at 20 stations in Beijing are used.

In China, the visibility data at stations were obtained in different ways before and after 2013. Before 23 January 2013, visibility was measured for meteorological purposes as a quantity estimated by a human observer. Since then, the observations of visibility have been transformed to instrumental measurements of the meteorological optical range (MOR). MOR is defined as the length of the path in the atmosphere required to reduce the luminous flux of a collimated beam from an incandescent lamp at a color temperature of 2700 K to 5 percent of its original value; the luminous flux is evaluated by means of the photometric luminosity function of the International Commission on Illumination (WMO, 2008). According to the theoretical calculation (WMO, 1990; 2008), the transformation formula between the visual estimate and the instrumental measurement is:

$$\frac{VIS_{Instrumental}}{VIS_{Artifical}} = \frac{(1/\sigma)\times\ln(1/0.05)}{(1/\sigma)\times\ln(1/0.02)} \approx 0.766 \qquad (\sigma\text{: extinction coefficient})$$

It is necessary to address these data and maintain their consistency before analysis. In this study, the visibility observations during 2013-2016 are transformed to be comparable with the earlier visual estimations.

Haze is a multidisciplinary phenomenon, occurred occasionally. In different fields, haze is represented by different variables, e.g. visibility and humidity in meteorology and PM2.5 concentration in environmental science. In general, haze occurrences in meteorology are defined based on the observations of relative humidity and visibility with specified criteria, which vary among organizations (e.g. World Meteorological Organization and UK Met Office) and empirical analyses (e.g., Wu, 2006; Vautard et al., 2009; Ding and Liu, 2014). In the present study, we adopted a widely used comprehensive method based on weather phenomenon, visibility and relative humidity. A haze day is defined if a haze weather phenomenon is recorded with a daily mean visibility below 10 km and a daily mean relative humidity below 90%. Early studies found that haze could be separated from fog by setting the relative humidity to be below 90% (Schichtel et al., 2001; Doyle and Dorling, 2002). A persistent haze event (PHE) is defined if haze is recorded at more-than-one sites in the region for 4 consecutive days. The number of persistent haze days is calculated as the sum of the

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics
Discussions

days during the PHEs.

2.2 Global climate observations

The daily and monthly data of the wind, geopotential height, specific humidity, sea level pressure and air temperature from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) for the period of 1980-2017, at 2.5° resolution (Kalnay et al., 1997) are used for the analysis of atmospheric conditions during the PHEs. We also used the monthly data of meridional wind at 850 hPa for the period 1900-2010 from the 20th Century Reanalysis (20CR) version 2, at 2°resolution (Compo et al., 2011) and the ECMWF Atmospheric Reanalysis of the 20th Century (ERA-20C) at 1° grid resolution (Poli et al., 2016). The monthly SST data used are from the Hadley Center Sea Ice and Sea Surface Temperature (HadISST) dataset, version 1.1, at 1°resolution (Rayner et al., 2003) for the period 1900-2011.

The dominant feature of the winter monsoon over East Asia is the northwesterly winds in the lower troposphere (Fig.1). Severe haze usually occurs when the surface to mid-lower troposphere northwesterlies weaken or even reverse to southerlies, indicating weakened EAWM (Niu et al., 2010). The unusual southerlies at 850 hPa over eastern China were found to be critical to the gathering of PM2.5 in Beijing (Cai et al., 2017). Thus, we proposed a practical EAWM indicator, that is, the southerly winds at 850hPa over the region (30-50°N, 105-125°E) outlined in Figure 1. An extreme southerly day is defined if the regional mean anomalous 850 hPa meridional winds exceeds 2 standard deviations above the boreal winter average in the region.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

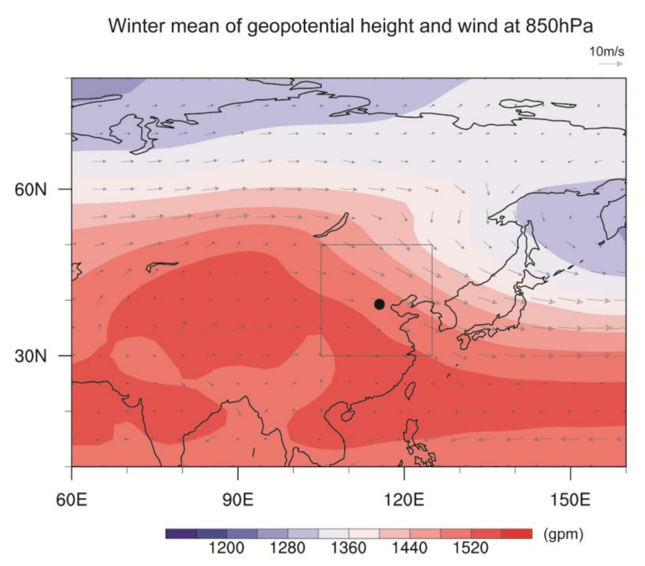

Fig. 1. Climatological mean of winter wind (vector, units: ms^{-1}) and geopotential height (shading, units: gpm) at 850 hPa over East Asia during 1980-2016. The outlined region (30-50 ° N, 105-125 ° E) is used to calculate a regional mean climatological background around Beijing (black dot).

2.3 Ensemble Empirical Mode Decomposition (EEMD)

In present paper, the EEMD method is applied to separate the multidecadal-to-centennial timescale variations of the SSTA time series over the northwestern Pacific. The EEMD method is an adaptive time-frequency data analysis technique developed by Wu et al. (2007) and Wu and Huang (2009). It is an efficient way to separate specific timescale variations in the original data series. The EEMD method is a refinement of the Empirical Mode Decomposition (EMD) method, which emphasizes the adaptiveness and temporal locality of the data decomposition (Huang et al. 1998; Huang and Wu 2008). With the EMD method, any complicated data series can be decomposed into a few amplitude-frequency modulated oscillatory components, called intrinsic mode functions (IMFs), at distinct timescales.

The main steps of the EEMD analysis in this study are as follows (Qian, 2009): (1) add a random white noise series with an amplitude 0.2 times the standard deviation of the data to the target time series to provide a relatively uniform and high-frequency extreme distribution, allowing the EMD to avoid the effect of potential intermittent noise in the original data; (2) decompose the data with the added white noise into IMFs using EMD; (3) repeat steps 1-2 for

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

1000 times, but with distinct random white noise series added each time; and (4) obtain the mean IMFs of the 1000 ensemble results to produce the final results.

Via EEMD, the mean SSTA series over the northwestern Pacific (120°–150°E, 26°–40°E) for the winter during 1900-2009 is decomposed into a nonlinear secular trend (ST) and 5 major timescales of IMFs (figure not shown). The multidecadal variability (MDV) is represented by the fifth IMF, with an oscillatory period between half and one century.

3 Results

3.1 Increasing PHEs in Beijing from 1980 to 2016

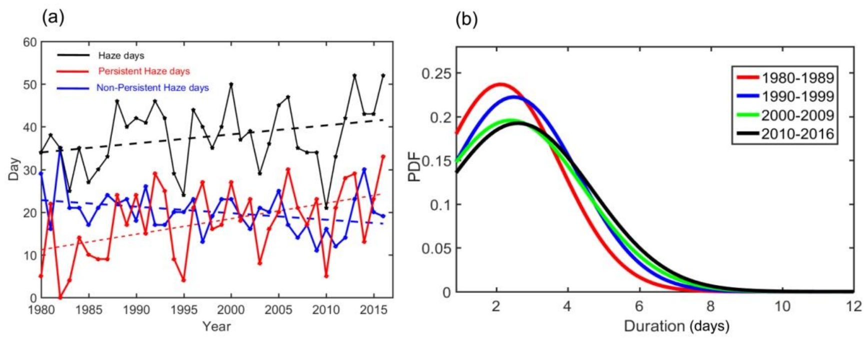

Fig. 2. (a) Number of haze days (black), persistent haze days (red) and non-persistent haze days (blue) in winter in Beijing during 1980-2016. Dashed lines show the least squares trends. (b) The Probability Distribution Function (PDF) of the duration (unit: days) of haze events in Beijing for each decadal period during 1980-2016.

As shown in Fig. 2a, the number of haze days in Beijing exhibits large inter-annual variability with a non-significant increasing trend (black curve in Fig. 2a), consistent with previous studies (e.g., Chen and Wang, 2015). However, the number of persistent haze days in Beijing exhibits a significant increasing trend, while that of the non-persistent haze days exhibits a significant decreasing trend, significant at the 0.05 level. Therefore, it is the number of persistent haze days that has been increasing during the past decades. The PDF of the duration of haze events in Beijing (Fig. 2b) indicates that most haze events lasted for about 3 days. However, the probability of haze events lasting for 1-3 days decreased, while that of the longer events increased from the 1980s to the present. The PHEs lasting for more than 4 days have increased remarkably. The duration of haze events have tended to be longer in the past decades.

3.2 Meteorological conditions for PHEs

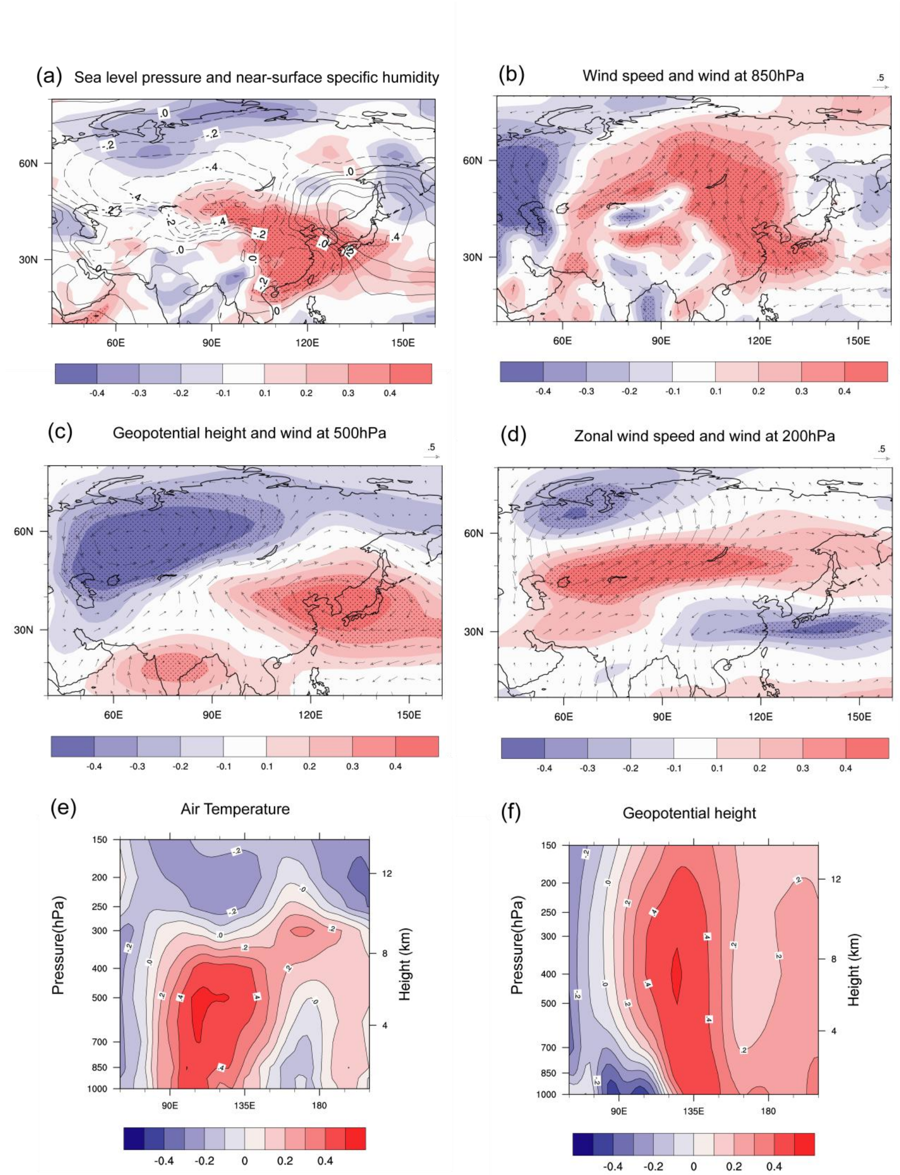

Fig. 3. The correlation coefficients between the number of persistent haze days and (a) sea level pressure (contour) and near-surface specific humidity at 1000 hPa (shading); (b) wind (arrows) and wind speed (shading) at 850 hPa; (c) wind (arrows) and geopotential height (shading) at 500 hPa; (d) wind (arrows) and zonal wind speed (shading) at 200 hPa; (e) vertical profile of air temperature at 40 °N; and (f) vertical profile of geopotential height at 40 °N in winter during 1980-2016, based on the monthly NCEP/NCAR reanalysis data. The linear trend is removed before calculating the

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

correlation. The black dots indicate significant changes at the 0.05 level using the t-test.

Figure 3 depicts the correlation coefficients of the anomalous variables of atmospheric circulation from near-surface to upper troposphere with the number of persistent haze days in Beijing in the winter during 1980-2016. In the lower troposphere (Fig. 3a), most of China is covered by an anomalous low-pressure system, adjacent to an anomalous high over the western Pacific, suggesting weaker-than-usual northerly winds from the mid-high latitudes. Consequently, North China is covered by the anomalous southerlies, resulting in a significant decrease in wind speed (Fig. 3b). Southerly winds bring warm and moist air from the south to the north part of China, creating favorable moisture conditions for haze occurrences (Fig. 3a). At 500 hPa, East Asia is mainly dominated by an anomalous high (Fig. 3c), representing a shallow East Asian Trough. The associated northwesterlies exist to the north rather than the south of Beijing, limiting the cold and dry northwesterly flows to Beijing and reducing the wind speed in Beijing. These atmospheric circulation patterns are favorable for severe haze occurrences, as partly discussed in previous studies (Chen and Wang, 2015; Yin and Wang, 2016; Cai et al., 2017). At the upper troposphere 200 hPa, the East Asian jet stream shifts northward (Fig. 3d) with enhanced zonal circulation in the high latitudes and weakened meridional circulation over East Asia. This pattern indicates weak cold air activity around Beijing. The decreased zonal wind in the middle latitudes favors the maintenance and enhancement of the pollutant convergence needed for the haze occurrences. The vertical profiles of air temperature and geopotential height at 40°N around Beijing suggest an abnormal pressure system over the northwestern Pacific region (40°N, 120-155°E) with anomalously warm temperature and high geopotential height from 850 hPa to 300 hPa (Fig. 3e and f). This anomalous vertical structure of atmosphere is also favorable for stagnant weather conditions and gathering of pollutants in the atmospheric boundary layer around Beijing.

3.3 Variations of extreme southerlies and its relationship with PHEs

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics
Discussions

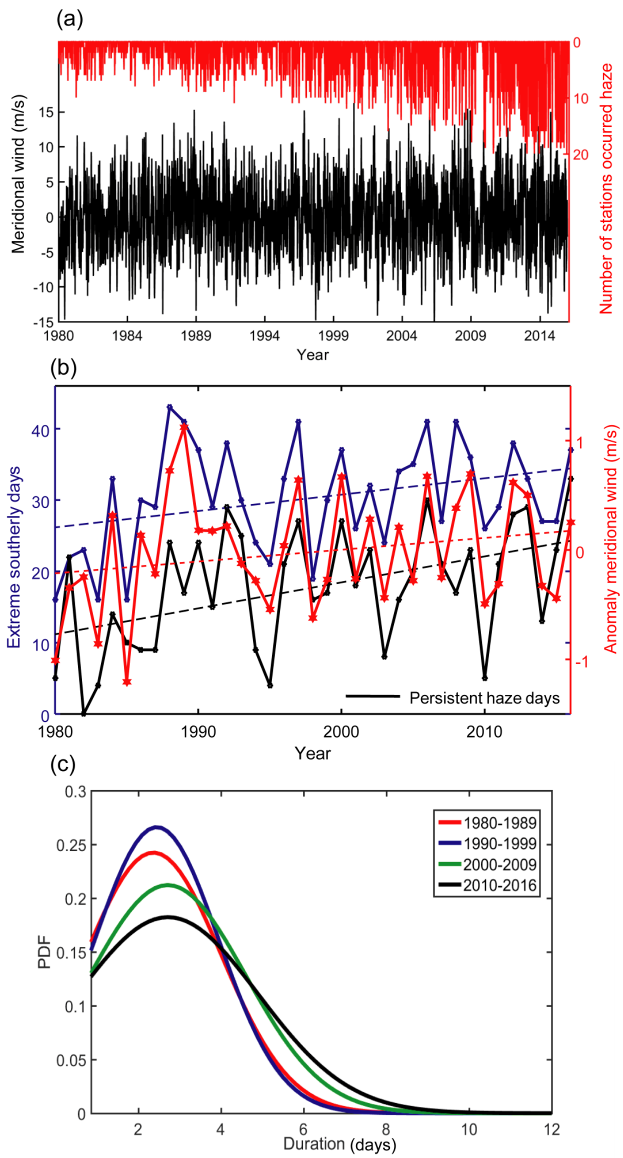

Fig. 4. (a) Number of stations where haze is recorded in Beijing (red) versus daily normalized meridional wind at 850 hPa over the study region (30-50 °N, 105-125 °E) (black) in winter during 1980-2016. (b) Anomalous meridional wind (red), number of extreme southerly days (blue) and persistent haze days (black) in winter during 1980-2016. Dashed lines show the least squares trends. (c) The Probability Distribution Function (PDF) of the duration (unit: days) of extreme southerly episodes for each

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

decade during 1980-2016.

The weakening of the EAWM system was considered to be responsible for the changes of meteorological conditions in Fig. 3 (Niu et al., 2010; He, 2013; Wang and He, 2013; Yin and Wang, 2016). During PHEs, the northerly winter monsoon weakened and brought less cold and dry air to the region, favorable for the formation and maintenance of haze. According to present analysis, the meridional wind anomalies at 850hPa in North China could be one of the most effective conditions for haze occurrence.

As shown in Fig. 4a, daily meridional wind anomalies are notably correlated with the number of haze stations in winter during 1980-2016. The correlation coefficient is 0.43, at $\alpha = 0.01$ level. It suggests that the southerlies well correspond to the haze occurrence in Beijing. The time series of the meridional wind anomalies in winter exhibits strong interannual variability with a non-significant increasing trend (red lines in Fig. 4b). However, the number of extreme southerly days exhibits a significant increasing trend (significant at the 0.05 level) and it has a significant positive correlation coefficient of 0.70 (0.66) with the number of persistent haze days in Beijing with (without) trends, significant at $\alpha = 0.01$ level. The PDF of the duration of extreme southerly events indicates that most of the extreme southerly episodes lasted for 3 days (Fig. 4c). However, the probability of the extreme southerly episodes lasting for 1-3 days is decreasing, while that of the longer episodes is increasing. The change in the extreme southerlies corresponds well to that of the persistent hazes in Beijing. Clearly, the higher probability of the longer extreme southerly episodes was underlying the increasing occurrences of PHEs in Beijing.

3.4 Linkages between SSTA over the NW Pacific and meridional wind anomalies since 1900

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics Discussions
Open Access

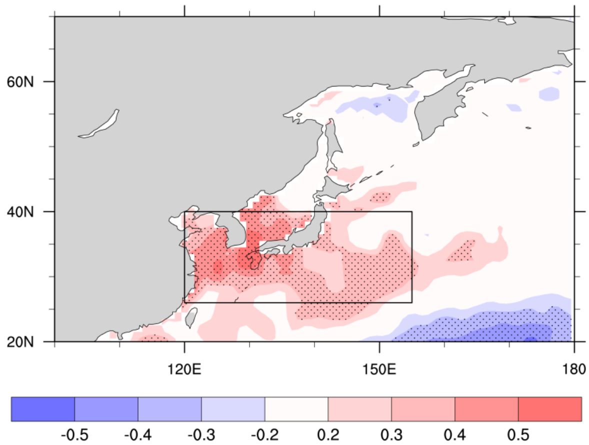

Fig. 5. The correlation coefficients between SSTA in the northwestern Pacific and the number of extreme southerly days in winter in North China during 1980-2011. The linear trend is removed before calculating the correlation. The black dots indicate significant correlation at the 90% confidence level using the t-test.

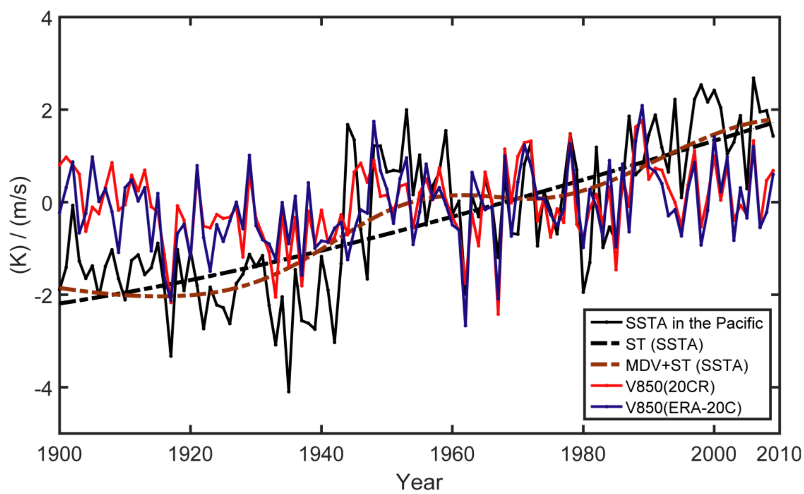

Fig. 6. Time series of the normalized SSTA in the northwestern Pacific (black), meridional wind anomalies at 850 hPa in North China from 20CR (red) and ERA-20C

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics Discussions
Open Access

(blue) during 1900-2009. The climatic mean is calculated for the period 1961-1990. The black dotted curve is the secular trend (ST); the brown dotted curve is the combination of ST and the multidecadal variability obtained via EEMD.

As shown in Fig. 5, there is a positive SSTA zone in the subtropical northwestern Pacific (120–155 °E, 26–40 °E). This suggests that the northerly winter monsoons in East Asia become weaker, with more extreme southerly episodes, when the subtropical northwestern Pacific is warmer. It is interesting to investigate this relationship over a longer period. As shown in Fig.6, over the past centennial period 1900-2009, SSTA in the subtropical northwestern Pacific and the meridional wind anomalies at 850 hPa over North China well co-varied, especially at the multidecadal timescale. The correlation coefficients are 0.46 (detrended: 0.42) and 0.51 (detrended: 0.53), based on the ERA-20C and 20CR data, respectively, all significant at $\alpha = 0.01$. During this period, the SSTA showed a warming secular trend. The combination of MDV and ST of SSTA exhibits a particular warming phase since the mid-1980s. As discussed above, this notable warming phase in the subtropical Pacific could lead to a weakened EAWM, with increasing number of extreme southerly episodes, and hence increasing PHEs in Beijing.

4. Conclusion and discussion

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Atmospheric Chemistry and Physics
Open Access
Discussions

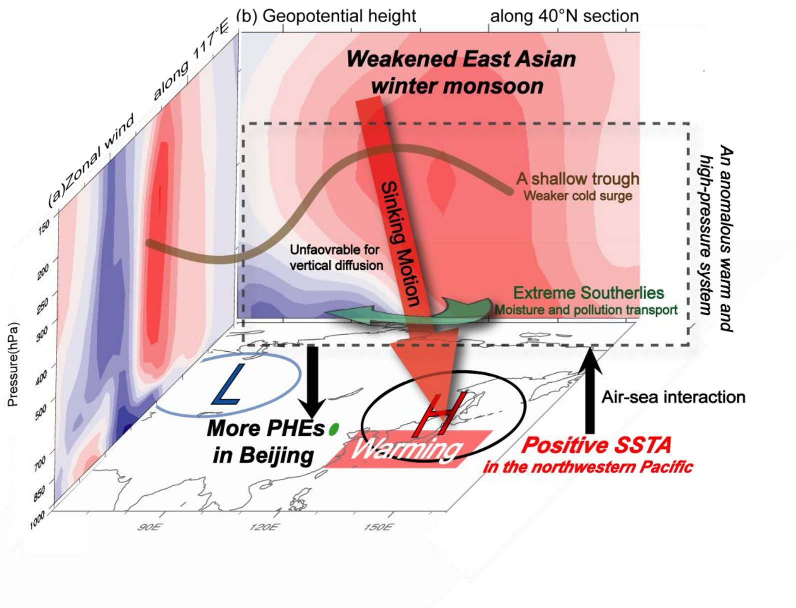

Figure 7. Schematic diagrams summarizing the dynamical linkage between positive SSTA in the northwestern Pacific, via the weakening East Asian winter monsoon system, and increasing PHEs in Beijing. The cross sections are correlation coefficients between meridional wind anomalies and vertical profile of (a) zonal wind at 117 °E and (b) geopotential height at 40 °N at 500 hPa in winter during 1980-2016. The latitude and longitude coordinates of Beijing (green dot in base map) is 40 °N, 117 °E. The letter "L" and "H" in base map demonstrate anomalous low-pressure and high-pressure system, respectively.

So far we have demonstrated the increasing frequency of PHEs in Beijing based on updated observations and the associated changes in large-scale atmospheric circulations during 1980-2016, and then explored the linkages of sea surface temperature in the northwestern Pacific in the past centennial period 1900-2009. The essential meteorological conditions favorable for the increasing PHEs in Beijing are associated with the weakening East Asian Winter Monsoon system, which is partly a consequence of the warming (positive SSTA) over the NW Pacific via air-sea interaction. Figure 7 illustrates such a dynamic mechanism.

There is a secular warming trend over the subtropical northwestern Pacific, consequently with anomalous high pressure or anti-cyclone system in the mid-lower troposphere over the region maintained via air-sea interaction. It would induce anomalous southerlies over the East Asian continent. Therefore, as a consequence, the EAWM system weakens. Particularly, in the lower troposphere, the weakening monsoons are more likely than before interrupted by persistent southerlies in North China, which bring warm and moist air from the south to the north of eastern China and create favorable moisture conditions for haze occurrences. In the mid-troposphere, the East Asian Trough tends to be shallower and prevent the associated northwesterlies from expanding towards the south of Beijing, hence favorable for gathering of pollutants around Beijing. These anomalous circulation patterns tend to cause sinking air motion in the mid-lower troposphere over Beijing, leading to stagnant weather conditions and gathering of pollutants in the atmospheric boundary layer. These changes in SSTAs and associated atmospheric circulation clearly contribute to the increasing PHEs in Beijing.

One of the most direct circulation factors for haze occurrences is weakened northerlies in the lower troposphere around Beijing. During 1980-2016, the change in the extreme southerlies corresponds significantly to that of the persistent hazes in Beijing. The higher probability of the longer extreme southerly episodes in the past decades was underlying the increasing occurrences of PHEs in Beijing. Furthermore, we found that over the past centennial period 1900-2009, the anomalous meridional winds at 850 hPa were positively correlated with the SSTA over the subtropical northwestern Pacific. Since the mid-1980s, a notable warming phase in the northwestern Pacific has weakened the East Asia winter monsoon system, increased the number of extreme southerly episodes in eastern China, and therefore contributed to the increasing PHEs in Beijing.

During the past centennial period 1900-2009, the SSTA in the northwestern Pacific showed a notable warming secular trend. In fact, the northwestern Pacific is one of the most stable warming regions, as a part of global warming during the last century (Zeng et al., 2001). IPCC (2013) has concluded that it is very likely that anthropogenic forcings have made a substantial contribution to the increase of global upper ocean heat content (0–700 m) as observed since the 1970s. Based on the results of 15 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), Cai et al. (2017) projected some circulation changes induced by increasing atmospheric greenhouse gases that might contribute to the increasing hazes in Beijing. The present paper suggests a more concrete observation-based mechanism for explaining how the changes in atmospheric circulation contribute to the increasing haze occurrences in Beijing.

Nevertheless, emissions of pollutants should also have contributed to increasing hazes in Beijing. It remains interesting to quantify contributions of pollutants emissions and climate change to the occurrences of PHEs in Beijing. Further studies are needed.

Data availability.

Atmospheric circulation data are available from the NCEP/NCAR data archive

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

(http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) and ECMWF data archive (https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets). SST data are downloaded from Met office Hadley centre observation datasets (https://www.metoffice.gov.uk/hadobs/hadisst/). The ground observations are from the National Meteorological Information Center of China (http://data.cma.cn/). The atmospheric composition data can be obtained from the authors.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements: This study was supported by the National Key Research and Development Program of China (2016YFA0600404), Beijing Natural Science Foundation (8161004), the Ministry of Science, Technology of China (IUMKY201725), Beijing Municipal Science and Technology Project (Z151100002115045), National Natural Science Foundation of China (41575010) and National Key Research and Development Program of China (2010CB428506).

References:

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

Chen, W. and Kang, L.: Linkage between the Arctic Oscillation and Winter Climate over East Asia on the Interannual Timescale: Roles of Quasi-Stationary Planetary Waves. Acta Meteorol. Sin. 30(5): 863-870. (in Chinese). 2006.

Chen, H. and Wang, H.J.: Haze days in north China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. J. Geophys. Res. 120, 5895-5909, 2015.

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N, Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessemoulin, P., BroNnimann, S., Brunet, M., Crouthamel, R.I., Grant, A.N., Groisman, P.Y., Jones, P.D., Kruk, M.C., Kruger, A.C., Marshall, G.J., Maugeri, M., Mok, H.Y., Nordli, O., Ross, T.F., Trigo, R.M., Wang, X.L., Woodruff, S.D., and Worley, S.J.: The twentieth century reanalysis project. Quart. J. Roy. Meteor. Soc., 137(654), 1-28. 2011.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

Ding, Y.H. and Liu, Y.J.: Analysis of long-term variations of fog and haze in China in recent 50 years and their relations with atmospheric humidity. Sci. China Earth Sci. 57, 3646, 2014.

Doyle, M., and S. Dorling., Visibility trends in the UK 1950–1997, Atmos. Environ., 36, 3161–3172. 2002

Gao, M, Guttikunda, S.K., Carmichael, G.R., Wang, Y., Liu, Z., Stanier, C.O., Saide, P.E. and Yu, M.: Health impacts and economic losses assessment of the 2013 severe haze event in Beijing area. Sci.Total.Environ. 511: 553-561. 2015.

Guo, J., Zhang, X., Wu, Y., Zhaxi, Y., Che, H., La, B., Wang, W. and Li, X.: Spatiotemporal variation trends of satellite-based aerosol optical depth in China during 1980-2008. Atmos. Environ. 45, 6802-6811. 2011.

He, H., Wang, X., Wang, Y., Wang, Z., Liu, J. and Chen, Y.:Formation mechanism and control strategies of haze in China. Bull.Chinese.Acad.Sci. 28 (3). 344—352. 2013

Hou, Q., An, X.Q., Wang, Y., Tao, Y. and Sun, Z.B.: An Assessment of China's PM10-related Health Economic Losses in 2009. Sci.Total.Environ. 435-436:61-65.2012.

Huang, N.E., Shen, Z., Long, S.R., Wu, M.C., Shih, H.H., Zheng, Q., Yen, N.C., Tung, C.C. and Liu, H.H.: The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis. Proc.Roy.Soc.London.Series.A. 454:903–995.1998.

Huang, N.E., Wu, Z.H.: A review on Hilbert-Huang transform: method and its applications to geophysical studies. Rev. Geophys. 46:RG2006. doi:10.1029/2007RG000228.2008

Huang, R.J., Zhang, Y.L., Bozzetti, C., Ho, K.F., Cao, J.J., Han, Y.M., Deallenbach, K.R., Slowik, J.G., Platt, S.M., Canonaco, F., Zotter, P., Wolf, R., Pieber, S.M., Bruns, E.A., Crippa, M., Ciarelli, G., Piazzalunga, A., Schwikowski, M., Abbaszade, G., Schnelle-Kreis, J., Zimmermann, R., An, Z., Szidat, S., Baltensperger, U., Haddad, I.E. and Prevot, ASH.: High secondary aerosol contribution to particulate pollution during haze events in China. Nature. 514, 218-222 . 2014.

Huang, R., Chen, J., Wang, L. and Lin, Z.: Characteristics, processes, and causes of the spatio-temporal variabilities of the East Asian monsoon system. Adv.Atmos.Sci. 29(5):910-942. 2012

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

IPCC.: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2013

Kalnay, Bayabkina, Sizov A.A., Zhukov, A.N. and Pryakhina.: The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc., 77, 437-470. 1996.

Li, Q., Zhang, R.. and Wang, Y.. Interannual variation of the wintertime foghaze days across central and eastern China and its relation with East Asian winter monsoon. Int. J. Climatol. 36, 346354, 2016

Liao, X., Zhang, X., Wang, Y., Liu, W., Du. J. and Zhao, L.: Comparative analysis on meteorological condition for persistent haze cases in Summer and Winter in Beijing. Environ. Sci. 35(6):2031-2044. (in Chinese). 2014

Li, S.L., Wang, Y.M. and Gao, Y.Q.: A review of the researches on the Atlantic Multidecadal Oscillation (AMO) and its climate influence. Trans Atmos Sci, 32(3):458-465. 2009

Lin, C., Yang, K., Qin, J., and Fu, R.: Observed Coherent Trends of Surface and Upper-Air Wind Speed over China since 1960. J.Clim. 26(9):2891-2903. 2013

Liu, J. and Diamond. J.: China's environment in a globalizing world. Nature，435，1179-1186, 2005

Niu, F., Li, Z.Q., Li, C., Lee, K.H. and Wang, M.Y.: Increase of wintertime fog in China: potential impacts of weakening of the eastern Asian monsoon circulation and increasing aerosol loading. J.Geophys. Res. 115, D00K20, 2010.

Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A.J., Vitart, F., Laloyaux, P., Tan, D.G.H., Peubey, C., Thepaut, J.N., Tremolet, Y., Holm, E.V., Bonavita, M., Isaksen, L. and Fisher, M.: ERA-20C: An atmospheric reanalysis of the 20th century. J.Clim, 29(11):160308090852005. 2016

Pope, C.A.III., and Dockery, D.W.: Health effects of fine particulate air pollution: Lines that connect, J. Air. Waste.Manage. Assoc., 56(6), 709–742. 2006

Qian, C.: A new method for the formation of climate anomaly reference frame and its validation and application (in Chinese). Doctoral Dissertation. Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, pp. 13–24. 2009

Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L., Rowell, D.P., Kent, E. and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

temperature since the late nineteenth century. J. Geophys. Res. Atmos.108 (D14):1063-1082. 2003

Schichtel, B. A., R. B. Husar, S. R. Falke, and W. E. Wilson., Haze trends over the United States 1980–1995, Atmos. Environ. 35, 5205–5210. 2001

Sun, J.Q., Wu. S. and Ao. J.: Role of the North Pacific sea surface temperature in the East Asian winter monsoon decadal variability. Clim.Dyn. 46(11-12):3793-3805. 2016

Sun, Y., Jiang, Q., Wang, Z., Fu, P., Li, J., Yang, T. and Yin, Y.: Investigation of the sources and evolution processes of severe haze pollution in Beijing in January 2013. J. Geophys. Res. Atmos. 119(7): 4380-4398. 2014

Sun, Z., An, X., Yan, T. and Hou, Q.: Assessment of population exposure to PM10 for respiratory disease in Lanzhou (China) and its health-related economic costs based on GIS. Bmc.Public.Health,. 13(1):1-9. 2013

Tang, G., Zhu, X., Hu, B., Xin, J., Wang, L., Munkel, C., Mao, G. and Wang, Y.: Impact of emission controls on air quality in Beijing during APEC 2014: lidar ceilometer observations. Atmos. Chem. Phys. 15(21):12667-12680. 2015

Vautard, R., P. Yiou, and G. Oldenborgh., Decline of fog, mist and haze in Europe over the past 30 years, Nat. Geosci., 2, 115–119. 2009. doi:10.1038/NGEO414.

Wang, H.J., Chen, H.P. and Liu, J.: Arctic sea ice decline intensified haze pollution in eastern China. Atmos. Ocean. Sci. Lett. 8, 19. 2015

Wang HJ and He SP.: The increase of snowfall in northeast China after the mid-1980s, Chin. Sci. Bull., 58(12), 1350–1354. 2013

Wang, L.T., Wei, Z., Yang, J., Zhang, Y., Zhang, F.F., Su, J., Meng, C.C. and Zhang, Q.: The 2013 severe haze over southern Hebei, China: model evaluation, source apportionment, and policy implications. Atmos. Chem. Phys. 14(6): 3151-3173. 2014

Wang, X.P., and Mauzerall, D.L.: Evaluating impacts of air pollution in China on public health: Implications for future air pollution and energy policies, Atmos. Environ., 40(9), 1706–1721. 2006

Wang, Y.S., Zhang, J.K., Wang, L.L., Hu, B., Tang, G.Q., Liu, Z.R., Sun, Y., and Ji, D.S.: Researching significance, status and expectation of haze in Beijing-Tianjin-Hebei region. Advances in Earth Science, 29(3), 388–396. (in Chinese). 2014b

Wang, S.Y., Yao, L., Liu, Z.R., Ji, D.S., Wang, L.L, and Zhang, J.K.: Formation of haze pollution in Beijing—Tianjin—Hebei region and their control strategies. Bull. Chinese Acad. Sci., 28(3)353-363. 2013

World Meteorological Organization (WMO). Guide of Meteorological Instruments and Methods of Observation. Eos Transactions, 55. 2008

World Meteorological Organization.: The First WMO Intercomparison of visibility Measurement: Final Report (D. J. Griggs, D. W. Jones M. Ouldridge, W. R. Sparks) Instrument and Observing Methods Report No. 41, WMO/TD.401, Geneva. 1990b

Wu, D., More discussions on the differences between haze and fog in city (in Chinese), Meteorology, 32, 9–15. 2006

Wu, P., Ding, Y.H. and Liu, Y.J.: Atmospheric Circulation and Dynamic Mechanism for Persistent Haze Events in the Beijing–Tianjin–Hebei Region. Adv.Atmos.Sci. 34(4):429-440. 2017

Wu, Z., Huang, N.E., Long, S.R., Peng, C.K.: On the trend, detrending, and variability of nonlinear and nonstationary time series. Proc.Natl.Acad.Sci. U.S.A. 104(38):14889–14894. doi:10.1073/pnas.0701020104.2007

Wu, Z., Huang, N.E.: Ensemble empirical mode decomposition: a noise-assisted data analysis method. Adv Adapt Data Anal 1:1–41. doi:10.1142/S1793536909 000047. 2009

Xie, Y.B., Chen, J., and Li, W.: An assessment of PM2.5 related health risks and impaired values of Beijing residents in a consecutive high-level exposure during heavy haze days [in Chinese], Environ. Sci., 35(1), 1–8. 2014

Xu, P., Chen, Y.F., and Ye, X.J..: Haze, air pollution, and health in China, Lancet, 382, 2067, doi:10.1016/S0140-6736(13)62693-8. 2013

Yang, S., Lau, K.M. and Kim, K.M.: Variations of the East Asian jet stream and Asian-Pacific-American winter climate anomalies. J Clim, 15: 306–325. 2002

Yin, Z. and Wang, H.: The relationship between the subtropical Western Pacific SST and haze over North - Central North China Plain. Int.J.Climatol, 36(10):3479-3491., 2016

Zeng, Z.M., Yan, Z.W. and Ye, D.Z.: Regions of most significant temperature trend during the last century. Adv Atmos Sci. 18 (4) 481-496. 2001

Zhang, L., Wang, T., Lv, M. and Zhang, Q.: On the severe haze in Beijing during January

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-757
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 21 November 2017

2013: Unraveling the effects of meteorological anomalies with WRF-Chem. Atmos. Environ. 104: 11-21. 2015.

Zhang, R., Jing, J., Tao, J., Hsu, S.C., Wang, G., Cao, J., Lee, C.S.L, Zhu, L, Chen Z, Zhao, Y. and Shen, Z.: Chemical characterization and source apportionment of PM2.5 in Beijing: seasonal perspective. Atmos. Chem. Phys. 13, 70537074. 2013

Zhang, R.H., Li, Q., and Zhang, R.N.: Meteorological conditions for the persistent severe fog and haze event over eastern China in January 2013. Sci. China Earth Sci., 57, 26–35. 2014

Zhang, Y., Zhang, P., Wang, J., Qu, E., Liu, Q. and Li, G.: Climatic characteristics of persistent haze event over Jingjinji during 1981-2013. Meteorology, 41(3). 311-318. (in Chinese). 2014

Zhou, Y., Wu, Y. and Yang, L.: The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China. Atmos. Environ. 44, 285-293. 2010.

Zhu, X., Tang, G., Hu, B., Wang, L., Xin, J., Zhang, J., Liu, Z., Munkel, C., and Wang, Y.: Regional pollution characteristics and formation mechanism over Beijing-Tianjin-Hebei area: a case study with model simulation and ceilometers observation, J. Geophys. Res. Atmos., 121, doi: 10.1002/2016JD025730. 2016

Zou, Y.F., Wang, Y.H., Zhang, Y.H. and Koo, J.H.: Arctic sea ice, Eurasia snow, and extreme winter haze in China. Science Advances, 3(3):e1602751. 2017