Environmental Research Letters

LETTER

Diminishing clear winter skies in Beijing towards a possible future

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Keywords: Beijing haze, East Asian winter monsoon, climate change, projection

Abstract
Severe haze during the winter season has been troubling the citizens of Beijing over the past few decades, and the trend seems to be continuing. However, occasionally such as the winter of 2017 (2017/12–2018/2), one would be amazed to see unusually few hazy days throughout the winter that brings memories of a long past. It is controversial to say whether such a nowadays-rare event is a result of policy-driven emission cuts or an opportunity brought about by natural climate variability. This paper investigates the probability of such anomalous atmospheric circulation events in winter from a climate perspective. Based on updated observations, only three winters during the past 38 years are found to be similar to that of 2017. These events were accompanied by a strong Siberian High to the north and cold anomalies in the mid-lower troposphere in association with a strong East Asian Trough, which favored the strengthening of northwesterly winds and effective ventilation. The occurrences of such favorable winter circulation anomalies are found to have decreased by about 50% from the 1st to the 2nd half of the 20th century. A further 60% [11.4%, 89.3%] reduction between 1951–2000 and 2050–2099 is projected by climate models under the IPCC’s Representative Concentration Pathway 8.5 scenario. Without serious cuts in pollution emissions, winters are projected to be dismal for the 20 million people of Beijing to a possible future under global warming.

1. Introduction

Rapid economic development and urbanization have caused widespread environmental issues in China. Air pollution is a particularly acute problem, as it affects the daily life of more than two-thirds of China’s entire population (Liu and Diamond 2005, Zhang 2017). Winter haze has been choking citizens across major cities, such as the capital (Beijing), which has culminated during haze episodes in the winters of 2013, 2015 and 2016 (Zhang et al 2014, Zhu et al 2016, Yin and Wang 2017, Li et al 2018a). Severe haze leads to a sharp decrease in visibility, causing traffic hazards and disruptions, and, hence, affecting economic activities (Huang et al 2014, Chen and Wang 2015, Li et al 2016). It also induces serious health problems, such as respiratory illness, heart disease, premature death and cancer (Pope and Dockery 2006, Wang and Mauzerall 2006, Silva et al 2013, Gao et al 2015). A recent study indicated a total economic loss of about CNY 400 billion caused by serious haze, accounting for 1% of China’s GDP in 2012, due to disease-induced working-time reduction across 30 Chinese provinces (Xia et al 2018).

Due to the challenge of such a problem, a variety of control measures have been taken since 2013, including the mandatory implementation of desulfurization, denitrification and other pollution-controlling facilities in factories (Liu et al 2017, Peng et al 2017). A recent analysis of China’s anthropogenic emissions from 2010 to 2017 suggested that the emission reduction rates had accelerated after the year 2013, as a result of China’s Clean Air Action since 2013 (Zheng et al 2018). Noticeable differences were made, but severe haze episodes persisted in the Beijing–Tianjin–Hebei region until the winter of 2017 (2017/12–2018/2). In 2015, 13 cities in the Beijing–Tianjin–Hebei region failed to meet the Chinese air quality standard for 47.6% of the year. During the winter of 2016, the concentrations of PM$_{2.5}$ and PM$_{10}$ were still 2.1 and 1.7
times higher than the National Ambient Air Quality Standards (GB3095–2012 guideline value (annual) of Grade II), respectively. However, the winter of 2017 was surprising, with a dramatic decrease in the number of hazy days over North China, particularly in Beijing. It is difficult to attribute this event to policy-driven emission cuts or natural climate variability. An observation-based study pointed out that there was no significant trend in the number of winter haze days in most parts of eastern China from 1973 to 2012, contrary to the two-and-half-fold increase in emissions of particulate matter and its precursors (PM emissions) in the same period (Mao et al. 2018). The large interannual climate variability can give rise to a large interannual variability in atmospheric pollution, even if emissions do not change. The impact of climate variability on air pollution may even exceed that of the changes in anthropogenic emissions (Wang 2018). An interesting question is: how likely winter climate conditions, such as those in 2017, will repeat in the future?

In general, haze refers to an atmospheric phenomenon caused by fine particulate pollutants from various sources under specific meteorological conditions (Wang et al. 2013, Wang et al. 2014). Meteorological conditions not only determine the extent of dispersion of pollutants (Ding and Liu 2014, Zhang et al. 2014, Li et al. 2016, Yin and Wang 2016), but also greatly influence the formation of secondary pollutants, which is an important part of haze formation in China (Huang et al. 2014, Peng et al. 2016, Wang et al. 2016). Meteorological conditions during haze episodes over North China are stagnant, and the weather is usually controlled by an anomalous low surface pressure system accompanied with abundant moisture conditions, weak surface winds and an inversion in the boundary layer (Tao et al. 2014, Zhu et al. 2016, Wu et al. 2017). The strength of the East Asian winter monsoon (EAWM) and its associated near-surface winds (Niu et al. 2010) and humidity (Chen and Wang 2015) are key factors that are strongly influenced by upstream conditions, such as Arctic sea ice (Wang et al. 2015, Zou et al. 2017), and downstream ones, such as the sea surface temperature anomalies (SSTAs) over the northwestern Pacific (Pei et al. 2018). Moreover, these are regulated by the El Niño Southern Oscillation (Zhao et al. 2018a) and the Pacific Decadal Oscillation (Zhao et al. 2016), among others. A case study comparing two extreme years between 2017 (best, clear winter) and 2016 (worst, hazy winter) emphasized the critical importance of the EAWM (Yan et al. 2018). However, the extreme extent or frequency of winter atmospheric circulation anomalies, such as those in 2017, remains unclear.

Recently, the possible influences of anthropogenic climate change on haze occurrences have been reported and are expected to induce more stagnant weather for increasing haze episodes in China (Cai et al. 2017, Zou et al. 2017, Li et al. 2018b). The human-induced enhanced atmospheric greenhouse effect is generally expected to increase atmospheric stagnation (Wu et al. 2013, Horton et al. 2014). A large number of climate simulations show that anthropogenic climate warming significantly increases the probability of monthly atmospheric patterns conducive to haze (Li et al. 2018b). The haze-conducive weather conditions for the region are projected to increase by 50% in frequency and 80% in persistence under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway 8.5 (RCP8.5) scenario (Cai et al. 2017). It is interesting to explore how much the anthropogenic climate warming can influence the occurrences of extreme atmospheric conditions favorable for clear winters in Beijing such as that of 2017. It is an important issue for local policymakers about pollution control with regard to climate change.

In this paper, we analyze the large-scale atmospheric circulation anomalies for extremely clear winters in Beijing such as those of 2017 from a climate perspective and investigate changes in their frequencies during the past and future. First, based on updated daily observations, we examine the linkage between the number of non-haze days in winter in Beijing and large-scale atmospheric circulation anomalies from surface to upper troposphere and propose a composite (atmospheric) dispersion index (CDI) to depict the comprehensive meteorological conditions for clear winter skies in Beijing. The circulation-based index CDI enables us to look back into the historical period based on atmospheric reanalysis data and to analyze future projections using climate models under the IPCC scenarios. Based on the long-term atmospheric reanalysis data, we then explore the changes in the probability distribution function (PDF) of the CDI and its component winter atmospheric circulation anomalies during the 20th century. Furthermore, climate projections for the late half of this century in 14 selected climate model runs from the Coupled Model Intercomparison Project phase 5 (CMIP5, Taylor et al. 2012) under a high-emission scenario (RCP8.5) are investigated. We describe the data and methods used in section 2, the results in section 3, and the discussion and summary in section 4.

2. Data and methods

2.1. Station data and definition of a haze day

The meteorological data used here are from quality-controlled station observations collected at the National Meteorological Information Center of China, including relative humidity, visibility and weather phenomenon records (http://data.cma.cn/). The data include four observations per day at 02:00, 08:00, 14:00 and 20:00 local time (LT). Consecutive records during the winter (December, January and February; DJF) from 1980 to 2017 at 20 stations in Beijing are used. For example, the winter of 1980 refers to the average of December 1980, January 1981 and February 1981.

In this study, a haze day at a station is defined if a haze phenomenon is recorded, with a daily mean visibility <10 km and daily mean relative humidity
<90%. A haze day in Beijing is defined if there is at least one (threshold number of $N = 1$) station with haze on the day. We calculated the correlation among the series of haze days with $N$ from 1 to 3, and that with the CDI (composite dispersion index, defined later), as shown in table S1 is available online at stacks.iop.org/EnvironResLett/13/124029/mmedia. The results indicate that all the correlation coefficients are significant at $\alpha = 0.001$. The different series of haze days (defined with $N = 1$–3) have similar interannual variability, although the increasing trend of the haze day series for $N = 1$ is relatively minor. Notable is that the correlation coefficients between the detrended series of haze days ($N = 1$–3) and CDI for the period 1980–2017 are almost the same (about 0.68). Therefore, using different threshold number ($N$) of stations to define a haze day in Beijing should have little influence on the main conclusions of this paper.

Visibility data at the stations were obtained differently before and after 2013. Before 2013, visibility was measured for meteorological purposes as a quantity estimated by a human observer. Since then, visibility has been observed by instrumental measurements. Pei et al (2018) adjusted these 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 paper, based on the updated observations, we extend the time series of winter haze days in Beijing from 1980 to 2017.

2.2. Atmospheric reanalysis datasets

Monthly data for wind speed, geopotential height, specific humidity, sea level pressure (SLP) and air temperature from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) during the period of 1980–2018 at a 2.5° resolution (Kalnay et al 1996, https://esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml) are used for identifying the atmospheric conditions for clear winters in Beijing.

In order to analyze long-term changes of the winter circulation conditions, we use the monthly data for the period 1900–2010 from the 20th Century Reanalysis (20CR) version 2 at a 2° resolution (Compo et al 2011, https://esrl.noaa.gov/psd/data/) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Atmospheric Reanalysis for the 20th Century (ERA20C) at a 1° grid resolution (Poli et al 2016, https://ecmwf.int/).

2.3. CMIP5 experiments

To examine how the atmospheric conditions for clear winters in Beijing respond to global climate warming in the future, we assess 31 CMIP5 model runs (table S1), in which monthly outputs are available and cover both the historical and future time under the RCP8.5 scenario. The CMIP5 simulations are available at https://cera-www.dkrz.de/WDCC/ui/cerasearch/. The historical simulations are forced by natural (i.e. solar radiation and volcanic aerosols) and anthropogenic (i.e. greenhouse gases, aerosols, ozone and land use) factors. The RCP8.5 simulations are run with the projected increases in atmospheric concentration of greenhouse gases, representing the high-emissions scenario. The simulated SLP, meridional wind, zonal wind and air temperature are used in this paper. To facilitate evaluating the performances of the models over East Asia, the CMIP5 data are interpolated to a common resolution of $2.5° \times 2.5°$, consistent with that of the NCEP reanalysis. Then, the pattern correlation coefficients of the climate mean (1971–2000) pattern in winter over eastern Asia (including SLP, meridional wind at 850 hPa, zonal wind at 500 hPa, and vertical air temperature at 40 °N) between the NCEP reanalysis data and the CMIP5 historical simulations are calculated. We selected 14 model runs for the following analysis, with all the pattern correlation coefficients exceeding 0.85 (table S2).

3. Results

3.1. Large-scale atmospheric features for a clear winter in Beijing

A statistical analysis of the number of haze days in winter in Beijing from 1980 to 2017 shows that there were only 19 haze days in the winter of 2017, a minimum over the past decades (Yan et al 2018). To help find out the most relevant large-scale circulation anomalies underlying such local extremely clear winter events, we calculate the correlation coefficients between the number of non-haze days in Beijing and the anomalous atmospheric variables from the near-surface to upper troposphere. The results in figure 1 depict the following atmospheric features corresponding to a clear winter in Beijing.

In the lower troposphere (figure 1(a)), the Siberian High is stronger than usual, leading to more frequent and intensified cold air surges from the mid-high latitudes into eastern China, with unfavorable (dry) humidity conditions for the formation of haze. The Siberian High intensity (SHI) is measured by a regional mean of the SLP within 47–60 °N, 53–95 °E (green box in figure 1(a)). Consequently, North China is covered by widespread anomalous northerly winds, indicating a strengthened EAWM, favorable for the clearance of pollutants around Beijing. A practical index for measuring the EAWM strength is the meridional wind speed anomaly at 850 hPa over eastern China (30–50 °N, 105–125 °E; green box in figure 1(b), referred to as V850 hereafter), similar to that proposed by Pei et al (2018).

In the mid-troposphere, the East Asian Trough strengthens, and the associated anomalous north-westerlies extend over North China, causing stronger cold and dry air flows over Beijing (figure 1(c)). These are favorable for the dispersion of pollutants around Beijing. The anomalous mid-tropospheric circulation
can be measured by the difference between the average zonal wind at 500 hPa to the northwest of Beijing (46–56°N, 53–105°E) and that to the south of Beijing (26–37°N, 100–135°E; green box in figure 1(c), hereafter referred to as U500). A negative U500 indicates a deepened East Asian Trough, with anomalous northwesterly flows favorable for clear winter in Beijing.

As to the cold anomalies in the lower troposphere over the region (figure 1(d)), these are consequently maintained by the anomalous high-pressure system in eastern China and the anomalous low-pressure system off the east coast (figure 1(a)), which lead to strengthened EAWM (cold northwesterlies) favorable for dispersion of pollutants in North China. Also, these lower-tropospheric cold anomalies are unfavorable for the development of an inversion in the boundary layer. For comparison, anomalous warmth in the lower troposphere is favorable for forming an inversion in the boundary layer and hence haze in the region (Zhang et al 2014, Chen and Wang 2015). The intensity of this vertical thermal structure is measured by the difference (ΔT) of temperature anomalies between the lower troposphere (850 hPa; 40°N, 95–125°E) and upper troposphere (250 hPa; 40°N, 106–126°E; green lines in figure 1(d)).

3.2. CDI for clear/hazy winters in Beijing

Overall, those atmospheric features can be synthesized as a comprehensive relationship between the clear/hazy winters in Beijing and large-scale atmospheric conditions. The correlation coefficients of the haze days in winter in Beijing with the indices of SHI, V850, U500 and ΔT are −0.59, 0.59, 0.66 and 0.51, respectively, all significant at α = 0.001. We then calculate a composite atmospheric index by adding the normalized time series of −SHI, V850, U500 and ΔT. This new index is normalized to its own climatology and then named as the CDI.

As figure 2 shows, the new index CDI has a significant correlation coefficient of 0.68 with the number of haze days in winter in Beijing. There are many climatic factors influential to the occurrence of haze in China, via modulating the atmospheric circulation over East Asia, e.g. solar radiation, Arctic Sea Ice and SSTAs over the oceans (e.g. Ramanathan et al 2001, Wild et al 2005, Wang et al 2015, Zhao et al 2016, Pei et al 2018, Zhao et al 2018a, 2018b, Li et al 2018c). The present paper is only to pick out probably the most direct circulation anomalies with regard to extremely clear winters in Beijing such as that of 2017, which are
The CDI for the winter of 2017 is $-1.83\sigma$, where $\sigma$ is the standard deviation of the CDI series for the period 1971–2000. According to figure 2, there were only two such extreme events in the past observations, 1983 and 2011, with CDI values smaller than $-1.83\sigma$. Therefore, the associated winter atmospheric anomalies in 2017 can be treated as an extreme climate event (with CDI not larger than $-1.83\sigma$). To explore the probability of such extremely anomalous winter conditions in the past and future in response to climate change, we need to investigate the PDFs of the relevant indices based on long-term observations and simulations.

Based on the long-term atmospheric reanalysis datasets (20CR and ERA20C), we calculate the correlation coefficients between the non-haze days in winter in Beijing and the anomalous atmospheric circulation variables for the period 1980–2009 (shown in figure S1) and the CDI series from 1900 to 2009. As figure 3 shows, the PDF of CDI shifts to the right from the 1st to the 2nd half of the last century, indicating an increased frequency of meteorological conditions conducive to hazy winters and a decreased one to clear winters in Beijing during the 20th century. The probability of the atmospheric circulation anomalies corresponding to those for clear winter in 2017 was 14%–16% during the first half of the 20th century, and decreased to 8% in the second half of the 20th century. An approximately 50% decrease of this type of
Table 1. The frequency of extreme winter atmospheric circulation anomalies (-SHI, V850, U500 and ΔT) beyond the case of 2017 in observations (20CR and ERA20C) and simulations (CMIP5).

| Frequency | SH (negative) | V850 | U500 | ΔT | CDI |
|-----------|---------------|------|------|-----|-----|
| Cir (2017) | -1.88σ       | −0.98σ | −1.82σ | −0.87σ | −1.83σ |
| 20CR      | 1901–1950     | 16%  | 42%  | 8%  | 50%  | 14% |
| Change    | 50%           | 43%  | 50%  | 44%  | 43%  |
| ERA20C    | 1901–1950     | 10%  | 54%  | 4%  | 70%  | 16% |
| Change    | 40%           | 59%  | 50%  | 63%  | 50%  |
| 14 runs in CMIP5 | 1951–2000 | 4.6% | 18.1% | 4.4%  | 31.1%  | 7.4% [4.9, 10.3] |
| Change    | 15.2%         | 15.3% | 2.3%  | 8.4%  | 2.7%[1.1, 4.4] |

σ: the standard deviation of the series for the period 1971–2000.

extreme climate events was evident in the 20th century, with its frequency of once six to eight years in 1901–1950 to once every 13 years in 1951–2000. The decrease of frequency is statistically significant (α = 0.05). Notably, the PDFs of the four component atmospheric circulation indices (i.e. -SHI, V850, U500 and ΔT) also shift in a consistent way (figure S2) from the 1st to the 2nd half of the last century. Corresponding changes of frequency of extremes in these component indices are shown in table 1. Overall, the occurrences of extreme values of these components (-SHI, V850, U500 and ΔT), such as those in 2017, decrease from the 1st to the 2nd half of the last century by 43%–50%.

3.3. Projection of CDI under global warming in the RCP8.5 scenario

First of all, we assess the performance of all the CMIP5 model runs available for the present study. We select 14 CMIP5 model runs, which relatively well reproduce the winter climate over East Asia for the historical period 1951–2000 (table S2). Then, we compare the PDFs of CDI and relevant winter atmospheric anomalies between the historical period (1951–2000) and the future (2050–2099) scenario. These experiments are forced by historical forces before 2006 and under the RCP8.5 (high-emissions) scenario from 2006–2100. To construct the CDI series in the historical and future simulations, the normalized anomalies of -SHI, V850, U500, ΔT and U500 are calculated based on the historical 30 year (1971–2000) climatology for each model.

As figure 4(a) shows, the PDF of CDI shifts towards larger CDI values from the historical period to the future scenario, suggesting a remarkable decrease of the favorable atmospheric conditions for clear winters in Beijing in the future period 2050–2099.

There are consistent changes in the component indices in the future scenario, towards a smaller frequency of anomalous strong Siberian High, northwesterly winds in North China, deep East Asia Trough and thermal instability of the lower troposphere (figures 4(b)–(e)). The probability of atmospheric circulation anomalies for extremely clear winters in Beijing (CDI not larger than −1.83σ) is about 7.4% [4.9%, 10.3%] in the current climate, but decreases to 2.7% [1.1%, 4.4%] in the future scenario. It means that the probability of such atmospheric circulation anomalies for clear winters in Beijing tends to decrease from the present to 2050–2099 under the RCP8.5 scenario by about 60% [11.4%, 89.3%]. Correspondingly, the frequency of such cases in each of the components (-SHI, V850, U500 and ΔT) tends to reduce by 15.2%, 15.5%, 47.7% and 73%, respectively (table 1). These results are supported by a strong inter-model consensus, as all the 14 model runs produced a decreased frequency of the atmospheric circulation anomalies with negative CDI values (table S3). The decrease in the frequency of negative CDI events is statistically significant at the 95% confidence level using the bootstrap method.

4. Summary and discussion

The winter of 2017 was surprising with unusually few haze days in Beijing, with regard to the increasing haze episodes in recent winters. The atmospheric circulation anomalies during the winter of 2017 were extremely favorable for the dispersion of pollutants in Beijing (Yan et al 2018). The present paper is to demonstrate some extremely anomalous large-scale climate conditions underlying this local ‘extreme’ event and to answer how likely such winter conditions will repeat with global warming in the future. Based on updated observations, we have depicted a set of winter atmospheric conditions from the near-surface to upper troposphere favorable for a clear winter in Beijing. These include a strong Siberian High to the north, strengthened northwesterly winds over North China and a deepened East Asian Trough in the mid-lower troposphere, accompanied by cold anomalies in the lower troposphere enhancing effective ventilation. We then design a CDI, obtained by a combination of the individual conditions, to facilitate comparative analyses of such extreme events between different periods of the last century and between the simulated historical and future climate. For the period
Figure 4. Probability density functions of CDI (a), negative SHI (b), V850 (c), U500 (d) and ΔT (e) in the historical (1951–2000, blue) and future (2050–2099, red) periods. The dotted line marks the value of CDI in 2017 (−1.83σ). The multi-model ensemble mean PDFs are shown, with shading for the 10%–90% confidence intervals derived from bootstrapping.
1980–2017, there were only three winters as extreme as that in 2017. The long-term reanalysis data show that the occurrences of such winter conditions have decreased by about 50% from the 1st to the 2nd half of the 20th century, i.e. from about once every 6–8 years to once every 13 years. The frequency of such extreme climate events also decreases from the historical (1950–1999) to future (2050–2099) according to 14 selected CMIP5 model runs under RCP8.5. An additional 63% [11.4%, 89.3%] reduction of extremely anomalous atmospheric conditions for clear winters such as that of 2017 is projected for the late of this century. There are uncertainties in these conclusions. Minor uncertainties for the observational period may arise from different datasets such as the 20CR and ERA20C reanalysis. Uncertainties in the climate model simulations are more considerable. As seen in table S3, some circulation indices (e.g. negative SHI, V850 and U500) in a few GCM simulations show an opposite trend to the results of the other model runs. Undoubtedly, climate projections with regard to clear/hazy winters in Beijing deserve further studies.

The haze intensity (pollution level) is also important, which largely depends on local emissions, regional pollutant transport, generation mechanisms for secondary pollution as well as meteorological conditions. The 2013 severe haze event in Beijing area is associated atmospheric circulations based on daily visibility data from 1960 to 2012 (Jacob and Winner 2009, Horton et al. 2014). Moreover, changes of the Arctic sea ice and boreal snowfall should also have effects on regional atmospheric circulation so as to worsen air pollution in China (Wang et al. 2015, Zou et al. 2017). These factors as revealed by different studies should probably work together to generate a diminishing trend of clear winter skies in Beijing.

Air pollution in China essentially arises from rapid urbanization and large-scale industrialization, being a serious issue affecting the health and quality of life of millions of people (OECD 2012, Silva et al. 2013, Wang and Mauzerrall 2006, Xia et al. 2018). This issue has become particularly severe for megacities, such as Beijing, during the past two to three decades. How to keep this issue to a minimum poses a paramount task for policy-makers. Controlling the sources of local emissions is ultimately the key factor, as global warming will potentially exacerbate the problem to some tipping point. Our results show that the occurrences of extremely anomalous atmospheric conditions such as those favorable for the clear winter of 2017 in Beijing have decreased by about 50% during the 20th century, and will have a further 60% reduction in the 2nd half of this century under a high-emissions scenario (IPCC RCP8.5). Although uncertainties remain especially in the climate model simulations, there have been increasing evidences suggesting increasing circulation conditions conducive to hazes in North China with global warming. Local policy-driven emission control might have made contribution to the clear winter of 2017, but additional actions are required about both local pollutants and global greenhouse gases emissions. Otherwise, the future of winter skies in Beijing will very likely be dismal.

Acknowledgments

Thanks are due to Dr Wu PL at the UK Met Office for discussion and improving the manuscript.

This study was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (CAS-XDA20020201), the National Key Research and Development Program of China (2016YFA0600404), Chinese Academy of Sciences International Collaboration Program (134111KYSB20160010 and 134111KYSB20160028) and the National Natural Science Foundation of China (41805082).

Competing financial interests

The authors declare no competing financial interests.

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