A dark October in Beijing 2016

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ABSTRACT

In recent years, haze pollution events in Beijing have increased sharply, and the haze pollution of Beijing in October 2016 reached a new high. Meteorological conditions are thought to have influences on the haze occurrence, yet the associated atmospheric circulation of haze in October and why the most severe haze pollution occurred in 2016 is still unclear. Here, the authors show through daily observation and reanalysis data that key regions of North Atlantic and North Pacific sea surface temperature (SST) anomalies may be the main factors for this most severe haze event. Since 2013, the SSTs of these two key regions have increased dramatically and reached a peak, which could have induced the severe haze pollution by affecting the Eurasia teleconnection (EU) and the North Pacific Oscillation, with these factors then providing favorable dynamic and thermodynamic conditions for haze development.

Introduction

The haze pollution events over Beijing and surrounding regions (hereafter BSR) (37°–43°N; 114°–120°E) have increased significantly since 2013 (Zhang, Li, and Zhang 2014; Li, Zhan, and Wang 2015), increasingly and negatively impacting people’s lives, society, and the economy, thus arousing widespread attention in China (Ding and Liu 2014; Chen and Wang 2015; Wang and Chen 2016).

It is well known that the primary reason for haze is pollutant emissions by human activities (Marrazzan et al. 2001; Chen et al. 2013; Wang et al. 2013; Wang and Chen 2016), and one very important emission source is coal consumption for heating in winter (Chen and Wang 2015). In northern China, heating begins in the middle of November. During this time, the energy consumption and pollutant emissions increase significantly, so the haze days of this region occur in winter more than other seasons (Chen and Wang 2015). In addition to pollutant emissions, atmospheric circulations are also another vital contributor for the occurrence of haze (Niu et al. 2010; Wang and Chen 2016). In recent years, studies have focused on atmospheric circulations and climatic affecting factors associated with haze growth. Several studies have indicated that local anti-cyclone anomalies around haze occurring regions and the EU pattern show a significant correlation with haze frequency (Yin and Wang 2015; Chen et al. 2015). In addition to the effects of atmospheric circulation, Wang, Chen, and Liu (2015) revealed that the decline of the preceding autumn’s Arctic Sea Ice (ASI) can intensify the winter haze pollution in eastern China.

In reviewing the previous research on haze pollution, it was found that most of the studies focused mainly on winter haze events. However, in addition to winter, the number of haze in October is also quite high (Chen and Wang 2015). October is a very special period because heating in northern China has not started yet, so the energy consumption...
level is very close to that of summer. In contrast to energy consumption, however, the monsoon circulation is changing from the summer monsoon to the winter monsoon in this region, so the impact of atmospheric circulation on haze events is more important during this period than at any other time and needs further investigation. Thus, in this study, we examine the occurrence of the most severe haze pollution event in October 2016, investigate the associated atmospheric circulations for haze in October, and provide a possible explanation for (1) the sudden increase of haze events since 2013 and (2) why the haze days in October 2016 reached a peak. These results may improve the haze prediction in the future.

Data and method

Thirty-four meteorological stations data surrounding Beijing such as precipitation, wind speed, relative humidity, and visibility are derived from the National Meteorological Information Center of the China Meteorological Administration during 1980–2016. These data values are given four times per day: 02:00, 08:00, 14:00, and 20:00 of local time (LT). Additionally, National Centers for Environmental Prediction daily Reanalysis data of atmospheric circulations with a horizontal resolution of 2.5° × 2.5° for the period from 1980 to 2016 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/, was also used to represent the climatic background of haze days (Kalnay et al. 1996). NOAA high-resolution daily sea surface temperature (SST) and sea ice concentration (ICES) data was used for the period 1981–2016 (Reynolds et al. 2007). For the definition of a haze day, the method is the same as employed in other studies (Chen and Wang 2015; Yin and Wang 2015; Wang and Chen 2016), which used the criteria of visibility being less than 10 km, relative humidity below 90%, no precipitation, and wind speed lower than 7 m s⁻¹, and if one of four times per day meets the criteria, the day is considered as haze day. The haze days number are the sum of the first twenty days of October and area averaged for all the sites.

Results

Figure 1 shows the time series of visibility and haze days in October during 1980–2016 over the BSR, and Figure 1(a)–(d) represents the variation of the four daily observed visibility data. According to these figures, only the visibility at 14:00 LT had a slight decrease before 2010; the other times had no tendency to decline and some even showed an increase. However, all the times show a significant decrease after 2010 and reach a new low in 2016, which is consistent with the daily mean visibility results (Figure 1(e)). Corresponding to visibility, haze days have almost no trend before 2010, but dramatically increase after 2010 and reach a peak in 2016.

Early studies (Chen and Wang 2015) have investigated the characteristics of atmospheric circulation associated with haze occurrences and indicate that the significant anomalies of atmospheric circulation could provide favorable/unfavorable dynamic and thermodynamic conditions for haze. The previous studies, however, mostly assessed the variation of seasonally averaged haze and mainly focused on the change of atmospheric background conditions related to winter haze occurrences. As indicated in Figure 1(e), the haze days of October over BSR reached a new high in 2016; therefore, further studies are needed to examine what is different regarding atmospheric circulation in October for this extreme case to occur.

By directly analyzing the circulations of October 2016, it was found that the West Pacific subtropical high was intensified and extended westward, allowing the warm moist airflow to move from the south to the BSR and high latitudes; this airflow was then cut off by cold air and formed a blocking high, with two cut-off lows on both sides. Corresponding to this atmospheric circulation (figure not shown), in the high latitudes, the Siberian high decreased, suggesting a reduction of cold air activities over BSR, and in the mid-latitudes, the southern warm moist airflow and pollutants were being constantly transported to this region, all of which led to severe haze pollution around Beijing. Figure 2 presents the atmospheric circulation anomaly in 2016 relative to the climatic mean of 1980–2015. In the lower troposphere, sea level pressure south of 50°N of China was dominated by a negative anomaly, with a positive anomaly over the Bohai Bay and Japan, implying a decrease of the northerly winds from the high latitudes (Figure 2(a)). Therefore, the region of BSR was under the influence of southern wind anomalies at 850 hPa (Figure 2(b)). In this case, the warm and humid airflows were easily transported into the BSR, which increased the surface temperature (Figure 2(a)) and relative humidity (Figure 2(c)), which is conducive to the haze occurrence. In the middle troposphere, the East Asian winter monsoon (EAWM) trough was weaker (Figure 2(c)), characterized by an anomalous high over the eastern part of East Asia. And an abnormally low pressure over the Siberian high region indicates that the Siberian high and EAWM are weakened, which then favored the formation of haze. Corresponding with a change in the middle level of 500 hPa, the upper westerly jet moved to the north with respect to the climatology, resulting in the cold air activities only in high latitudes, which is why the SAT presented an obvious low in the high latitudes (Figure 2(a)). All these dynamic and thermodynamic conditions together made the pollutants continuously accumulated over the BSR and
prevented them outward diffusion, which can promote the formation and maintenance of haze. In addition to horizontal transport diffusion, the vertical convection transport is another important method of pollutant diffusion. Figure 2(e) depicts the anomalous distribution of vertical air temperature in 2016 with respect to the climatology. As shown in Figure 2(e), there was a stronger increase of air temperature in the higher levels than in the lower levels, which meant an increased stability of the atmospheric stratification, resulting in the suppression of the vertical transport of aerosol particles and lead to haze events; in turn, because the aerosol can absorb and scatter the solar radiation, the aerosol concentration increase lead to the air temperature further increase, which then strengthens the stability of atmospheric stratification, thus forming a positive feedback that allows the haze pollution to last several days. With these air temperature anomalies, the vertical velocity represents weak ascension from 1000 to 925 hPa but sinking at almost all the levels above 925 hPa (Figure 2(f)). These convection conditions make near-surface pollutants converge to the BSR, while the upper conditions is unfavorable to pollutant diffusion, thereby causing and maintaining the haze events. All of these dynamic and thermodynamic anomalies led to the severest haze pollution in 2016.

So what made this year’s circulation so abnormal and made 2016 the most serious year for haze pollution? We further studied the external forcings of sea ice and SST. According to Wang, Chen, and Liu (2015), the ASI in autumn has a very strong negative correlation with winter haze activity in eastern China. Therefore, we analyzed the sea ice in August, September, and October and its relationship with haze days in October (figure not shown) and found that haze in October is different from winter haze and that the negative correlation between ASI and haze days in October does not exist. Consequently, the

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**Figure 1.** Variation of the four times of daily visibility for October: (a) 02:00 LT, (b) 08:00 LT, (c) 14:00 LT, (d) 20:00 LT, and the daily mean visibility (red line, km) and haze days (blue line, days); all the visibility and haze days are averaged over the BSR from 1980 to 2016.
cause of favorable atmospheric circulation for this severest haze event may not be the prophase and synchronous ASI anomalies. Figure 3(a) shows the correlation coefficient between haze days and global SST from 1981 to 2016. The shaded region indicates that the SST changes are significant at the 95% confidence level. It can be clearly seen that the number of haze days was significantly correlated with SST over the North Pacific and North Atlantic (Figure 3(b)). In corresponding the highly related SST region with haze, the SST anomaly distribution is very consistent in October 2016, which is very conducive to the occurrence of haze events over the BSR. Hence, we conclude that the severe haze over the BSR may be due to anomalous SST in the North Atlantic and North Pacific. We then define the two regions as key regions for haze events, where the North Pacific SST index is defined as the area-averaged SST of the region that passed the significance test (180°–130°W; 48°–60°N), and the North Atlantic SST index is defined as the positive anomaly region (18°W–5°E; 62°–72°N) minus the negative anomaly region (20°–50°W; 45°–58°N). The influence of SST on the atmospheric circulation in the key region was analyzed and compared with the atmospheric circulation related to haze. Figure 3(c) displays the correlation between haze days and the HGT in 500 hPa. There is a distinct EU or Scandinavian pattern (SCP) (Bueh and Nakamura 2007) across the Eurasian continent, where Scandinavia is an anomalous high, the Siberian is an anomalous low, and there is a high anomaly over the BSR. Such an HGT anomaly distribution is consistent with the anomalies in 2016 (Figure 3(d)) and is in close agreement with previous results (Zhang, Li, and Zhang 2014; Chen and Wang 2015). From Figure 3(a) and (b), it can be seen that the SST in the two key regions may be the external force for haze over the BSR. Figure 3(e) and (f) show the correlation distributions related to the North Pacific and the North Atlantic indices, respectively, both of which yield a very consistent wave train, as shown in Figure 3(a) and (b), that is, the key region's SST can influence haze events by affecting the EU/SCP anomaly, which affects the dynamic and thermodynamic background of haze occurrence. In
addition, the relationship between the SST in September and the haze event in October was analyzed. The results are in agreement with the corresponding period. The relationship is significant. The early SST can also influence the haze event by affecting the EU, which indicates the importance of the key region's SST in the entire process.

According to previous studies (Peng et al. 1995; Frankignoul, Czaja, and L’Heveder 1998; Czaja and Frankignoul 2002), the change of SST over the North Atlantic Ocean can affect the local atmospheric circulation through air-sea interactions, and then the atmospheric circulation anomaly will in turn affect the SST and form a positive feedback. As the teleconnection wave source location of EU/SCP, the change of the North Atlantic atmospheric circulation can influence the EU/SCP pattern significantly. Therefore, when SST anomalies occur in the North Atlantic, the anomalies of the atmospheric circulation associated with the SST can influence the variation of the EU/SCP pattern and ultimately affect the climate change and haze events over the BSR. On the other hand, for the SST in the North Pacific, many studies also have shown that the SST has a significant effect on the atmospheric circulation (Minobe et al. 2008; Kwon et al. 2010; Ogawa et al. 2012; Smirnov et al. 2015; Chen et al. 2016), especially the autumn and winter SST in the North Pacific (Frankignoul and Sennéchael 2007). Recently, Zhou et al. (2015) used daily observational SSTs to force a high-resolution atmospheric general circulation model and found that the North Pacific SST can significantly affect the atmospheric circulation by influencing the atmospheric storm activity in the extratropical ocean. To further verify the impact of SST on atmospheric circulation in the extratropical North Pacific, the difference between the SST and SAT in 2016 was studied; it was found that the Gulf of Alaska SST was higher than the SAT (figure not shown), so the sensible heat flux transport was from the ocean to the atmosphere, which is consistent with previous results showing that the ocean can influence the atmospheric circulation. The vector in Figure 3(d) shows the wave activity flux at 200 hPa in October 2016. It can be seen that there was significant energy in the middle and high latitudes of the North Pacific, which was transported to the North Atlantic wave source region via the Polar Regions; this then changed the EU/SCP pattern and ultimately affected the haze event. Previous
SSTs affected haze events after 2013, an 11-year running correlation between the key regions' SST indexes and the haze days is shown in Figure 4 (a). A positive correlation is found between the North Atlantic SST index and the haze days during 1981–2016. That is, when the SST of the northern part of the North Atlantic key region is an anomalous high and the southern part's SST is low, conditions are favorable for haze occurrence. Compared to the North Atlantic SST, the SST of the North Pacific's key region has no relationship with the number of haze days before 1995, and then the SST has a significant negative correlation with the haze days during 1996–2005; however, after 2005, this reversed into significant in-phase changes. Meanwhile, the two key regions' SST indices also exhibit an in-phase change after 2005, and the simultaneous change affects the haze events. From the temporal evolution of the three curves, the North Pacific SST index, the North Atlantic SST index, and the haze day time series, a similar conclusion to Figure 4(a) can be obtained, and most importantly, with the steep increase in haze days since 2013, the characteristic of the two SST indices also showed a sharp rise, with both of them reaching their peak in 2016. On the basis of Figure 4(a), the SST in the two key regions and haze days show synchronous

![Graph showing correlation between SST and haze days](image_url)

**Figure 4.** Upper panel indicates the correlation between the North Pacific SST index and haze days (red line), the North Atlantic SST index and haze days (green line), and the two SST indices of the North Pacific and North Atlantic (blue line) in a sliding window 11 years wide. The horizontal lines represent the 95% and 99% confidence level. Lower panel shows the temporal evolution of the North Pacific SST index (red line), the North Atlantic SST index (green line), and haze days (blue line). The vertical line indicates the year 2013.

studies have indicated that the North Pacific atmospheric circulation, SST, and sea ice can significantly influence the Asian-Pacific region climate change (Fan 2007a, 2007b; Wang, Sun, and Fan 2007; Xu, Fan, and Wang 2015; Chen et al. 2015). According to Figure 3(d), another southward energy transfer can be seen propagating from the high latitude North Pacific to the subtropical high region, corresponding to the HGT field spanning from the negative anomaly to the positive anomaly, which is also consistent with the North Pacific Oscillation (NPO) change; that is, when the Aleutian Low is strengthened, the subtropical high is also strengthened. These changes are conducive to Bohai Bay being dominated by an anomalous high, thus leading to the occurrence of haze.

From Figure 1(e), we see a sharp increase in the frequency of haze days over the BSR after 2013, but the study shows that China's energy consumption had only a very slight increase, with the 2014 levels actually lower than 2013 (Mathews and Tan 2015); thus, in addition to emissions, the steep rise in the number of haze days may be caused by other factors. As described above, the changes of SST in key regions of the North Atlantic and North Pacific have a very important effect on haze occurrence over the BSR. To analyze how the key region
changes after 2005, so the SST increased significantly after 2013 and reached a new high in 2016, which led to the haze pollution over the BSR increasing significantly after 2013 and the strongest haze pollution event in 2016.

Conclusions and discussions
From the severest haze event that occurred over the BSR in October 2016, the present study analyzed the changed characteristics of atmospheric circulation, ICES and SST related to this severe haze event by using daily observational data. It was found that the occurrence of haze was closely related to changes of atmospheric circulations. In October 2016, the EU/SCP teleconnection wave train was significantly strengthened. Corresponding to the change of EU/SCP, the Siberian high pressure weakened and the EAWM trough decreased, which made the Bohai Bay become dominated by an anomalous high. This weakened horizontal circulation was unfavorable to cold and dry air transport from the north and beneficial to collecting pollutants with the warm and humid airflow from the south region, leading to haze events. In the vertical direction, the increase of air temperature in the low troposphere was smaller than in the upper-middle troposphere, which resulted in stable atmospheric stratification that suppressed convection and weakened the vertical mix, which was then unfavorable to the diffusion of pollutants. Finally, both the horizontal and vertical dynamic and thermodynamic anomalies provided favorable conditions for the maintenance and development of haze over the BSR.

Further analysis indicates that the key regions of the North Atlantic and North Pacific SST anomalies may be the main reason for this severe haze event. It was found that the SST of the two regions tended to change synchronously after 2005, and both of them can cause the EU/SCP teleconnection wave train to change, which affects the circulation related to the haze events over the BSR. In addition, the SST in the North Pacific can also affect haze by influencing the change of the NPO. Since 2013, the two key regions’ SSTs increased sharply and reached a historical new high in 2016, which led to the haze days over the BSR rising significantly after 2013 and reaching a peak in 2016. However, more studies are needed to determine why the SST increased so quickly after 2013 and why the relationship between the key region of the North Pacific and haze days has an inter-decadal abrupt change.

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