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Possible influence of atmospheric circulations on winter hazy pollution in Beijing-Tianjin-Hebei region, northern China

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Abstract

Using the daily records derived from the synoptic weather stations and the NCEP/NCAR and ERA-Interim reanalysis data, the variability of the winter hazy pollutions (indicated by the mean visibility and number of hazy days) in Beijing-Tianjin-Hebei (BTH) region during the period 1981 to 2015 and its relationship to the atmospheric circulations in middle-high latitude were analyzed in this study. The winter hazy pollution in BTH had distinct inter-annual and inter-decadal variabilities without a significant long-term trend. According to the spatial distribution of correlation coefficients, six atmospheric circulation indices (I_1 to I_6) were defined from the key areas in sea level pressure (SLP), zonal and meridional winds at 850 hPa (U850, V850), geopotential height field at 500 hPa (H500), zonal wind at 200 hPa (U200), and air temperature at 200 hPa (T200), respectively. All of the six indices have significant and stable correlations with the winter visibility and number of hazy days in BTH. Both the visibility and number of hazy days can be estimated well by using the six indices and fitting and the cross-validation with leave-N-out method, respectively. The high level of the prediction statistics and the reasonable mechanism suggested that the winter hazy pollutions in BTH can be forecasted or estimated credibly based on the optimized atmospheric circulation indices. However, we also noted that the statistic estimation models would be largely influenced by the artificial control of a pollutant discharge. Thus it is helpful for government decision-making departments to take actions in advance in dealing with probably severe hazy pollutions in BTH indicated by the atmospheric circulation conditions.

1 Introduction

Beijing-Tianjin-Hebei (BTH) region is located in northern China, with approximately 110 million residents and 216 000 km^2 in size. As the rapid progress of urbanization and industrial development over the past three decades, the BTH region has become

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one of China's most economically developed regions and the third economic engine in China. Recently, the Chinese government has been promoting the integration of the three neighboring regions to optimize the industrial layout and improve the allocation of resources. Undoubtedly, the BTH region is becoming more and more important in China or even the world economy in the future. However, the rapid economic growth and urbanization have increased the level of air pollution in recent decades (Streets et al., 2007; Chan and Yao, 2008; Wang et al., 2009, 2010; Gao et al., 2011). Most of eastern China has frequently suffered from severe haze or smog days in recent years, especially in the BTH region. For example, the continuously hazy pollutions in January 2013 greatly threatened human health and traffic safety (Kang et al., 2013; Wang et al., 2013). Roughly speaking, the hazy pollution can be attributed to two aspects: pollutant emissions to the lower atmosphere from fossil fuel combustion or construction and favorable meteorological conditions. Meteorological conditions are controlling the occurrence of hazy pollution (Wu, 2012; Zhang et al., 2013). Specifically, weather conditions play an essential role in the daily fluctuation of air pollutant concentrations (Zhang et al., 2015).

At present, many studies have focused on the physical and chemical properties of pollutants in Beijing and other cities (Feng et al., 2006; Yu et al., 2011; Xu et al., 2013; Zhao et al., 2013). And also studies demonstrated the influence of weather conditions or synoptic situations upon air pollutions (Zhao et al., 2009; Zhang et al., 2015). They elucidated clearly the formation and chemical composition of air pollutants and the dominant meteorological factors on hazy days or during heavy pollution in Beijing and its neighboring areas. On the other hand, some studies demonstrated that the hazy pollution occurring in the BTH region could be strongly affected by the local atmospheric circulations including sea–land and mountain–valley breeze circulations and the planetary boundary layer height (Lo et al., 2006; Liu et al., 2009; Chen et al., 2009; Miao et al., 2015). Recently, Wang et al. (2015) suggested that the reduction of autumn Arctic sea ice leads to anomalous atmospheric circulation changes which favor less cyclone activity and more stable atmosphere and leading to more hazy days in eastern

China. Moreover, Wang et al. (2013) showed that east China suffered from severe hazy pollutions in January 2013 may be due to a sudden stratospheric warming over the mid-high latitude of Northern Hemisphere, which lead to an anomalous steady atmosphere dominated in northern China. Thus, it is interesting to examine whether the winter hazy pollution in BTH has been influenced by other known or unknown atmospheric circulations or teleconnections in the mid-high latitude of the Northern Hemisphere and whether there are some potential circulations that can be used for the forecast or evaluation of the winter hazy pollution in BTH. To date, it is not clear about these questions, and a few studies have been performed to explore these issues.

Owing to a lack of long-term instrumental records for air pollutant concentration, the understanding of the evolution of air pollution and their relations to atmospheric circulations is limited. In this paper, we intend to use the atmospheric visibility and the number of hazy days derived from the synoptic meteorological stations to denote the evolution of hazy pollution in the BTH region since 1980s. Many studies demonstrated that, in the absence of certain weather conditions (e.g., rain, fog, dust and snowstorm), the visibility is an excellent indicator of air quality because its degradation results from light scattering and absorption by atmospheric particles and gases that can originate from natural or anthropogenic sources (Baumer et al., 2008; Chang et al., 2009; Sabetghadam et al., 2012; Baddock et al., 2014), although visibility was influenced comprehensively by airborne pollutants and meteorological parameters such as relative humidity, wind speed, temperature, pressure and solar radiation (Wen and Yeh, 2010; Deng et al., 2014; Zhang et al., 2015).

The main purpose of this study is to examine the possible relations between the atmospheric circulations and the winter hazy pollution (the mean visibility and mean number of hazy days) over the BTH region and investigate the possible physical mechanism, which could be useful for a prediction of the winter hazy pollution and could provide a scientific support to the government to take effective measures in advance to reduce or control the pollutant emission in case of an anomalous circulations leading to a serious hazy pollution in the region. This paper is organized as follows. Section 2 describes the data and method used. Section 3 shows major results and discussions. Conclusion is summarized in Sect. 4.

2 Data and methods

2.1 Research area and station data

The atmospheric visibility recorded at the 19 synoptic meteorological stations located in the research area from 1 January 1980 to 28 February 2015 were used (Fig. 1). The visibility by human observers is recorded by four times (02:00, 08:00, 14:00 and 20:00 LT, Beijing) or three times (08:00, 14:00 and 20:00 LT, Beijing) per day. A good continuous monitoring operation was maintained throughout the entire period, with the missing data rates for the 19 stations varying from a minimum of 1.7 % to a maximum of 2.1 %, with a mean 1.9 %. On the other hand, the distribution of the stations is relatively uniform, indicating that the mean visibility or hazy days is a good representative for the whole BTH region.

In the present study, the days with visibility ≤ 5 km and relative humidity < 90 % at 14:00 p.m. LT were defined as hazy days, except the special weather phenomena occurred at this moment including rain, fog, dust and snow (Schichtel et al., 2010; Wu et al., 2014). The mean number of hazy days ($\overline{\text{NHD}}$) of each winter in the BTH region can be calculated by:

$$\overline{\text{NHD}} = \frac{1}{n}\sum_{i=1}^{n} N_i \qquad (1)$$

where n is the number of stations (here $n = 19$), N denotes the number of hazy days in a station in each winter (December, January and February). The mean visibility ($\overline{\text{Vis}}$)

of each winter in the BTH region can be calculated by:

$$\overline{\mathrm{Vis}} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{m}\sum_{j=1}^{m}V_{ij}\right) \qquad (2)$$

where n is the number of stations (here $n = 19$), m is the number of valid days in winter. It should be noted that the winter in 1981 consists of December 1980, January and February 1981, and so on.

2.2 Reanalysis data

The global NCEP/NCAR reanalysis data of the monthly sea level pressure (SLP), zonal and meridional winds at 850 hPa (U850, V850), geopotential height field at 500 hPa (H500), zonal wind at 200 hPa (U200) and air temperature at 200, 150, 100 and 70 hPa (T200, T150, T100, T70) with a $2.5^\circ \times 2.5^\circ$ spatial resolution from January 1980 to February 2015 were used (Kalnay et al., 1996). Moreover, in order to obtain a higher spatial resolution in the BTH region, the ERA-Interim reanalysis data of the monthly relatively humidity (RH), vertical speed (W), zonal (U) and meridional (V) winds from 1000 to 500 hPa (16 pressure levels in total) and the boundary layer height (BLH) with a $0.125^\circ \times 0.125^\circ$ spatial resolution confined to the area 33–45° N and 110–122° E were also used (Dee et al., 2011).

2.3 Analysis method

For the statistical and atmospheric circulation analyses carried out in the study, the common statistical methods such as the composite analyses and the least square regression and the Pearson correlation analyses with a two-tailed Student's t test were applied in this research. A principal component analysis (PCA) was also used to extract the principal mode of multiple time series. Moreover, in order to reduce the possible effects of low-frequency variation or long-term trends and to examine whether or not the correspondence between the two time series on inter-annual time-scale is stable, the high-frequency (< 10 yr) correlation of the high-pass filtered time series was also tested for time series analyses (Gong and Luterbacher, 2008; Zhang et al., 2010).

3 Results and discussions

3.1 Evolution of the winter visibility and hazy days in the BTH region

The regional mean visibility and number of hazy days in winter in BTH were presented in Fig. 2. As expected, the visibility was negatively correlated to the number of hazy days with the raw and high-frequency (< 10 yr) correlation coefficients between them of −0.91 and −0.93, respectively. Both of them are significant at the 0.01 level ($p < 0.01$ for short). More hazy days generally denote lower mean visibility in winter due to the light scattering and absorption effects of air pollutants (Baumer et al., 2008; Sabetghadam et al., 2012). There are intense inter-annual fluctuations in both the visibility and the number of hazy days over the entire period of 1981 to 2015. The decadal fluctuations can be also distinguished for both the visibility and the number of hazy days throughout the entire period. A significant reducing trend of visibility ($p < 0.05$) and increasing trend of number of hazy days ($p < 0.01$) dominated in the 1980s. And then, the visibility experienced an increasing trend in 1990s and a decreasing trend since 2001, and the hazy days showed an anti-phase changes, but none of them are statistically significant with exception of the number of hazy days trend in 1990s ($p < 0.05$). The mean visibility maximum in 1990s reached to 18.3 km (larger than the mean values of 17.9 km over the entire period); and the minimum number of hazy days in 1990s reached to 20.6 days (less than the mean values of 22.7 days over the entire period). However, the long-term trends of them are not statistically significant, although a weak reducing and increasing trends can be founded in the curves of winter visibility and number of hazy days, respectively.

3.2 Relationship between hazy pollution and atmospheric circulations

We first examined the correlation coefficients between the visibility and number of hazy days and the most common atmospheric teleconnection or oscillation indices over the mid-high latitude of Northern Hemisphere (see Table 1), which could affect the winter climate variability over China, such as the Arctic Oscillation (AO), the Northern Atlantic Oscillation (NAO), the Pacific/North American pattern (PNA), the Eurasian pattern (EU), the Western Pacific pattern (WP) and the Siberian High (SBH) (Wallace and Gutzler, 1981; Zhang et al., 2009; Gong and Ho, 2012). It can be seen that both of the raw ($r1$) and high-frequency ($r2$) correlations show that the visibility and number of hazy days are correlated weakly with the winter AO, NAO and PNA. However, the visibility is highly positively correlated with EU, WP and SBH; and the number of hazy days is highly negatively correlated with EU, WP and SBH, most of them are significant at the 0.01 or 0.05 level.

Furthermore, the general characteristics of spatial distribution of the correlation coefficients between visibility and number of hazy days in BTH and the major meteorological fields from surface to tropopause in Northern Hemisphere including SLP, U850, V850, H500, U200, T200, T150 and T70 were also examined (Figs. 3 and 4). Owning to a generally anti-pattern for the number of hazy days, thus only the correlation maps with visibility were analyzed for simplicity. In SLP (Fig. 3a), a positive correlation center dominated most of East Asian continent, while a negative correlation center dominated the area from northeast Asia to northwest Pacific, respectively. This spatial pattern may reflect the effects of land–sea thermal contrast on the lower troposphere condition over BTH region. The pressure increasing in East Asian continent and decreasing in area from northeast Asia to northwest Pacific suggest that they favor the visibility increase in the BTH region in winter, and vice versa. In UV850 (Fig. 3b), an anomalously anticyclonic and northerly pattern are predominant most of Siberia and eastern China. This suggests that an anomalous northerly advection from Siberian to eastern China improve the winter visibility in the BTH region. In H500 (Fig. 3c), there exist a "–+–" wave train pattern along the Eurasia-west Pacific in the mid-high latitude, extending from the central-eastern Europe through Siberia to north China-Korean peninsula-Japan-northwest Pacific Ocean, similar to the EU pattern (Wallace and Gutzler, 1981). This pattern implies that a deepening of East Asian trough and a weakening of blocking will favor the winter visibility increase in the BTH region. In U200 (Fig. 3d), there also exist a wave train pattern from northwest Russia through Siberia to northwest Pacific Ocean. This pattern may imply that the south (north) of East Asian Jet stream strengthened (weakened) coincided with the anomalous ascending (sinking) motions occurred in the south (north) of the Jet stream entrance at the upper troposphere, which will lead to a strengthening northerly appeared in the lower troposphere. Hence it is not conducive to the accumulation of pollutants over BTH region in the winter.

Besides the lower troposphere, previous studies suggested that the anomalous stratospheric warming over the Northern Hemisphere led to the severe hazy pollutions in east China in January 2013 (Wang et al., 2013). Here, the spatial distribution of the correlation coefficients between visibility and the temperature from the upper troposphere to lower stratosphere at 200 hPa (T200), 150 hPa (T150), 100 hPa (T100) and 70 hPa (T70) were checked. Negative correlations are found from eastern Siberia to the northern North Pacific including Alaska in T200, T150, T100 and T70, respectively (Fig. 4), with the biggest correlation in T200 (Fig. 4a). The significantly negative correlation suggest that the warming in this area would indicate a decreasing of winter visibility, namely a worsening of hazy pollutions in the BTH region.

Based on the above analyses, we wonder whether the meteorological variables in the significant correlation areas can be used to predict or evaluate the variability of the winter visibility and hazy pollutions in the BTH region. Thus, the six indices for atmospheric circulations or teleconnections were defined based on the key regions shown in the previous correlation maps as listed in Table 2. We computed the raw and high-frequency correlation coefficients of the winter visibility and number of hazy days in BTH and the six atmospheric circulation indices. All of the six indices (I_1 to I_6) show highly positive or negative correlations with the winter visibility and number of hazy days, with significance at the 0.01 level (Table 3). Moreover, we note that most of the high-frequency correlations are larger than the raw correlations except the correlations between visibility and I_1. This suggests that the links between the air quality in BTH and the circulations indices are very stable from year to year. The significantly positive or negative correlations should be a reflection of the physical response mechanisms between them, which will be discussed in the latter section.

3.3 Predictions for visibility and number of hazy days based on the circulation indices

In order to assess the prediction capability of the six circulation indices for the winter hazy pollutions in BTH, the winter mean visibility and number of hazy days were estimated by applying a multivariate regression method with the least square estimate. The estimated curves by the fitting and the cross-validation with a leave-one-out method were displayed in Fig. 5. Intuitively, both of the fitting curves and the cross-validation curves are fairly consistent with the observed winter mean visibility and number of hazy days over the last three decades. The raw and high-frequency correlation coefficients between the observed and the fitting visibility (number of hazy days) are 0.88 (0.78) and 0.86 (0.77), respectively. All of them are significantly at 0.01 level. A good fitting does not mean that there must be stable relationships between the dependent variable and explanatory variables. Thus we emphasized testing the stability of the statistic models by means of the Leave-*N*-out cross-validations. The statistics for the cross-validation estimations were listed in Table 4, including the explained variance (r^2), the standard error (SE), and reduction of error (RE). Previous studies suggested that RE is an extremely rigorous verification statistic because it has no lower bound, $\mathrm{RE} > 0$ indicating the skillful estimation, $\mathrm{RE} > 0.2$ indicating the reliable estimation and $\mathrm{RE} = 1.0$ indicating a perfect estimation (Fritts, 1976; Gong and Luterbacher, 2008; Zhang et al., 2010).

The statistics for both the visibility and number of hazy days are generally stable (no sharply increase or decrease) when *N* increased from 1 to 11 (more than 30 %

sample removed in regression models), although the r^2 and RE (SE) slightly decreased (increased) with the increasing of N. For the visibility, the r^2 varied from 52.5 to 62.7 % with an average of 57.6 %, the SE varied from 0.74 to 0.84 with an average of 0.79, the RE varied from 0.49 to 0.61 with an average of 0.55. For the number of hazy days, the r^2 varied from 31.1 to 41.5 % with an average of 35.2 %, the SE varied from 3.37 to 3.66 with an average of 3.54, the RE varied from 0.23 to 0.38 with an average of 0.30. The mildly changes of these statistics suggest that the statistic models between the given atmospheric circulations and the hazy pollution indicators are stably even in the case of parts of sample missed. On the other hand, we noted the statistics for the visibility estimations are generally better than that for the number of hazy days estimations in all tests. However, the minimum values of r^2 and RE for the number of hazy days estimations are still lager than 30 % and 0.2, respectively. Based on these statistics, it can be concluded that the predictions for the winter visibility and number of hazy days in the BTH region based on the circulation indices are overall reliable during the entire period, especially for the mean visibility. That is to say, the winter hazy pollutions in BTH can be evaluated or estimated well by the optimized atmospheric circulations.

The relatively larger errors for the estimated values referred to the observed visibility and number of hazy days have been found since the winter in 2009 (Fig. 5). We re-computed all the statistics for the period 1981 to 2008, the results displayed that all the values of r^2 and RE (SE) for visibility and number of hazy days predictions increased (decreased) much more than the entire period (Table 4), suggesting that the statistic estimation models are much more stable and reliable before 2009. Why did the prediction efficiency of the statistic estimation models decrease in the last few years? It can be distinguished that the estimations for the winter mean visibility are distinctly lower (higher) than the observed in the winters of 2009 and 2010 (2014), and vice versa for the number of hazy days. We speculated that these phenomena can be attributed to the fluctuations of pollutant emissions in part because the pollutant emissions over northern China around 2008 were controlled strictly by the Chinese government associated with the 2008 Olympic Games in Beijing (An et al., 2007; Zhang et al., 2010;

Gao et al., 2011). The decrease of pollutant emissions led to the improvement of air quality (increasing visibility and decreasing hazy days) in 2009 and 2010, although the atmospheric conditions remained the same and did not contributed to the spread and elimination of air pollutants. However, pollutant emissions especially in the areas of BTH rebounded after the Olympic Games, with the decrease in visibility and increase in hazy days in the BTH region around 2012 to 2014 to some extent (Zhang et al., 2015), although the atmospheric conditions remained relatively the same as before. From this result, it can be assumed the statistic estimation models for the winter mean visibility and number of hazy days would be largely influenced by an artificial control of pollutant discharge.

3.4 Possible mechanism of the circulations related to the winter hazy pollutions

In order to explore the possible mechanism and role of the investigated circulation indices on the winter visibility and number of hazy days in the BTH region, the links between the given large-scale atmospheric circulations and the local meteorological conditions, which have close relations with the hazy pollutions, were examined. For simplicity, a comprehensive index labeled as I_c was synthesized from the six individual circulation indices (I_1 to I_6) by applying a PCA method, namely the first principal component (PC1). The high values of the explained variance (64.4 % in PC1) indicated that the comprehensive index of I_c roughly reflect the integrated features of all the six indices. Thus, we used the I_c instead of the six individual indices in the following analysis. Generally, the positive (negative) I_c indicate the lower (higher) visibility and more (less) hazy days in the BTH region in winter.

First we examined the links between the I_c and the meteorological fields of SLP and H500 respectively. Based on the NCEP/NCAR reanalysis data, Fig. 6a and b present the climatological mean of SLP and H500 in winter averaged from 1981 to 2010, respectively. The changes of SLP and H500 in winter in association with a one-standard-deviation positive I_c during the winters 1981 to 2015 are shown in Fig. 6c and d, respectively. In the climatological mean fields, the BTH region were located in the trough of East Asian trough at the middle troposphere and in the ridge of Siberian–Mongolia high in SLP field, which indicate the northerly dominated the BTH region in winter. The regression maps show that the SLP decreased in the Siberian–Mongolia high areas and increased in the western Pacific in SLP and the geopotential height decreased in the most areas of Siberia and increased in the northern China to western Pacific. These patterns suggest that both the East Asian trough and Siberian high weaken with increasing I_c, that further implies that the winter cold air activity will be weaken and then lead to an anomalous steady atmospheric conditions in BTH and its adjacent areas in winter. Namely, the less strong Siberian high and East Asian trough and associated northerly winds in the low and middle troposphere will lead to a severe hazy pollution (lower visibility and more hazy days) due to the favorable meteorological conditions for the accumulation and chemical reaction of pollutants. Anyway, we wonder whether it is true as we speculated. We further examined the links between the comprehensive index of I_c and the local meteorological conditions which play direct roles in the formation of hazy pollutions, including the wind fields (Fig. 7), relative humidity (Fig. 8) and vertical velocity (Fig. 9) at the lowest troposphere (averaged from 1000 to 900 hPa with an interval of 25 hPa) and the boundary layer height (Fig. 10) based on the ERA-Interim reanalysis data.

Figure 7a Displays the climatological mean wind field averaged from 1000 to 900 hPa over the winter 1981 to 2010. At lower level, the northwesterly winds dominated the BTH, and the wind speed in Beijing, Tianjin and north of Hebei province was larger than that in the south of Hebei province. Figure 7b shows the composite (positive I_c winters minus negative I_c winters) wind field averaged from 1000 to 900 hPa over the winter 1981to 2015. In the composite wind field, the anomalous southeasterly winds dominated the BTH region instead of the northwesterly in the climatological mean wind field, indicating the weakening of the northwesterly significantly over BTH and its neighboring areas when I_c increased. Previous studies (Zhang et al., 2015) demonstrated the decreasing of wind speed is not conducive to the diffusion of air pollutants and easily lead to hazy pollutions in Beijing. It may be true for the whole BTH region. Thus, the increasing of I_c will lead to a decrease in the visibility and increase in the number of hazy days in winter over the BTH region.

Same as Fig. 7, Fig. 8a, b presents the climatology and composite relative humidity averaged from the lowest troposphere respectively. In the composite map, all the areas of BTH are covered by the positive values and most of them are significant at the 0.05 level. They indicate that the winter relative humidity was anomalous higher in the positive I_c years than that in the negative I_c years. As pointed in the Introduction, a high relative humidity is one of the important reasons for visibility degradation. Thus a positive I_c imply that a decreasing of visibility accompanied by the increasing number of hazy days may occur in the winter over BTH region. Figure 9a and b present the climatology and composite vertical speeds averaged from the lowest troposphere respectively. The positive (negative) values of vertical speed in unit of $\mathrm{Pa\,s^{-1}}$ denote sinking (ascending) motion. The climatological vertical speeds show that the downward air motions dominated the BTH region in the winter. In the composite vertical speed field, the most areas of BTH were covered by the significantly negative values, which suggested a less vertical exchanges of air occurred in this areas in the positive I_c winters. In other words, the increased I_c may result in a weaker vertical convection and forcing the lowest troposphere more stable. It's easy to understand the anomalous stabilization will lead to much hazy pollutions. Moreover, a similar result can be found in the planetary boundary layer height, which was reduced significantly in the most of BTH and its adjacent areas in the positive I_c winters (Fig. 10). The decreased boundary layer height will depress the air pollutants into a narrower air column in a certain area and then lead to an increasing of the pollutants concentration. Thus, a winter with the lower visibility and more hazy days in the BTH region would be expected in the case of the lower boundary layer height caused by the anomalously high I_c.

In view of the responses of the local surface winds, relative humidity, vertical motion and boundary layer to the comprehensive index of I_c mentioned above, the close relationships between the winter mean visibility and number of hazy days over BTH region and the given six atmospheric circulations are generally feasible in the physical mechanism. It is reasonable and reliable to estimate the winter hazy pollutions in the BTH region based on the seasonal forecast fields derived from climate simulation. Thus it will be helpful to provide scientific references for the governmental decisions in advance about the reducing or controlling of pollutants emission to deal with the probably severe hazy pollutions in the BTH region.

4 Conclusions

Using the daily visibility and number of hazy days recorded in the 19 meteorological stations and the NCEP/NCAR and ERA-Interim reanalysis data, the evolution of the winter hazy pollutions in the BTH region since 1981 and their possible relations to atmospheric circulations were examined in this study.

The results showed that the winter mean visibility has a significantly negative correlation with the number of hazy days and both of them show distinctly inter-annual variability during the entire period 1981 to 2015. The correlation coefficients between the winter hazy pollutions (the visibility and number of hazy days) and the most common atmospheric circulations over the mid-high latitude of Northern Hemisphere were re-examined. Results showed that the relations between the hazy pollutions in BTH and the winter AO, NAO and PNA were very weak, but they correlated significantly with EU, WP and SBH. Furthermore, the six new indices (I_1 to I_6) derived from the key areas in the fields of SLP, U&V850, H500, U200 and T200 were closely related to the winter hazy pollutions in BTH. We can estimate the visibility and number of hazy days by using the six indices and the fitting and the leave-*N*-out cross-validation methods, respectively. In general, the high level of the estimation statistics suggested the winter hazy pollutions in BTH can be estimated or predicted in a reasonable degree based on the optimized atmospheric circulation indices. However, we also noted that the statistic estimation models for the visibility and number of hazy days may be influenced by a prominent change of the pollutants emission artificially. Thus, it is valuable and significant for government decision-making departments to take actions in advance in dealing with the probably severe hazy pollutions in BTH indicated by the circulation conditions, such as to control the pollutants discharge.

In order to investigate the link processes between the hazy pollutions and the given atmospheric circulations more simply, a comprehensive index (I_c) was synthesized from the six individual circulation indices by applying a PCA method. The winter I_c increase appear to cause a shallowing of the East Asian trough at the middle troposphere and a weakening of the Siberian high pressure field at sea level, and then accompanied by a reduction (increase) of horizontal advection and vertical convection (relative humidity) in the lowest troposphere and a reduced boundary layer height in BTH and its neighboring areas, which are not conducive to the spread and elimination of air pollutants but favor the formation of hazy pollutions in BTH winter. In short, the reasonable link processes and the stable statistic relationships suggested that the atmospheric circulation indices can be used to predict or evaluate generally the hazy pollutions in BTH winter to some extent.

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Table 1. Correlation coefficients of visibility and hazy days and circulation indices.

		AO	NAO	PNA	EU	WP	SBH
Visibility	$r1$	−0.11	0.00	0.16	0.61[a]	0.40[b]	0.39[b]
	$r2$	0.05	0.22	0.16	0.71[a]	0.37[b]	0.36[b]
Number of hazy days	$r1$	0.13	0.13	−0.10	−0.51[a]	−0.47[a]	−0.32
	$r2$	−0.01	−0.11	−0.10	−0.70[a]	−0.56[a]	−0.37[b]

[a] Significant at the 0.01 level.

[b] Significant at the 0.05 level. The $r1$ and $r2$ terms indicate the raw correlation and high-frequency (< 10 yr) correlation, respectively.

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Table 2. List of the definition for the six circulation indices.

Index	Variable	Expression
I_1	SLP	SLP (38 ~ 50° N, 84 ~ 108° E) – SLP (36 ~ 52° N, 126 ~ 150° E; 24 ~ 40° N, 150 ~ 184° E)
I_2	$U_{850\,\text{hPa}}$	U_{850} (55 ~ 75° N, 40 ~ 110° E) – U_{850} (40 ~ 50° N, 45 ~ 75° E)
I_3	$V_{850\,\text{hPa}}$	V_{850} (32 ~ 64° N, 104 ~ 120° E)
I_4	$H_{500\,\text{hPa}}$	H_{500} (46 ~ 64° N, 50 ~ 92° E) – H_{500} (28 ~ 44° N, 16 ~ 28° E; 28 ~ 42° N, 120 ~ 156° E)
I_5	$U_{200\,\text{hPa}}$	U_{200} (42 ~ 52° N, 60 ~ 110° E) – U_{200} (64 ~ 76° N, 50 ~ 96° E; 28 ~ 36° N, 120 ~ 152° E)
I_6	$T_{200\,\text{hPa}}$	T_{200} (46 ~ 66° N, 146 ~ 196° E)

Table 3. Correlation coefficients of visibility and number of hazy days and circulation indices.

		I_1	I_2	I_3	I_4	I_5	I_6
Visibility	$r1$	0.73^a	0.57^a	-0.76^a	0.62^a	-0.59^a	-0.61^a
	$r2$	0.70^a	0.68^a	-0.80^a	0.72^a	-0.62^a	-0.62^a
Number of hazy days	$r1$	-0.60^a	-0.47^a	0.60^a	-0.47^a	0.52^a	0.60^a
	$r2$	-0.61^a	-0.65^a	0.69^a	-0.67^a	0.58^a	0.64^a

[a] Same as Table 1.

Table 4. List of the statistics for the Leave-*N*-out cross-validation estimations.

N	Period covering	Visibility			Number of hazy days		
		r^2 (%)	SE	RE	r^2 (%)	SE	RE
1	1981–2015	62.7	0.74	0.61	41.5	3.37	0.38
	1981–2008	87.1	0.42	0.87	53.9	2.56	0.52
3	1981–2015	56.8	0.80	0.54	34.3	3.57	0.28
	1981–2008	86.8	0.42	0.87	52.6	2.59	0.51
5	1981–2015	59.2	0.78	0.57	35.3	3.54	0.30
	1981–2008	86.8	0.42	0.87	46.7	2.75	0.43
7	1981–2015	59.0	0.78	0.56	37.5	3.48	0.33
	1981–2008	86.4	0.43	0.86	44.7	2.80	0.41
9	1981–2015	56.2	0.80	0.54	32.5	3.62	0.27
	1981–2008	84.2	0.46	0.84	40.8	2.90	0.36
11	1981–2015	52.5	0.84	0.49	31.1	3.66	0.23
	1981–2008	84.4	0.46	0.84	48.2	2.71	0.44

N denotes the number of sample removed in the cross-validation regressions; only the odd numbers of *N* were listed for short.

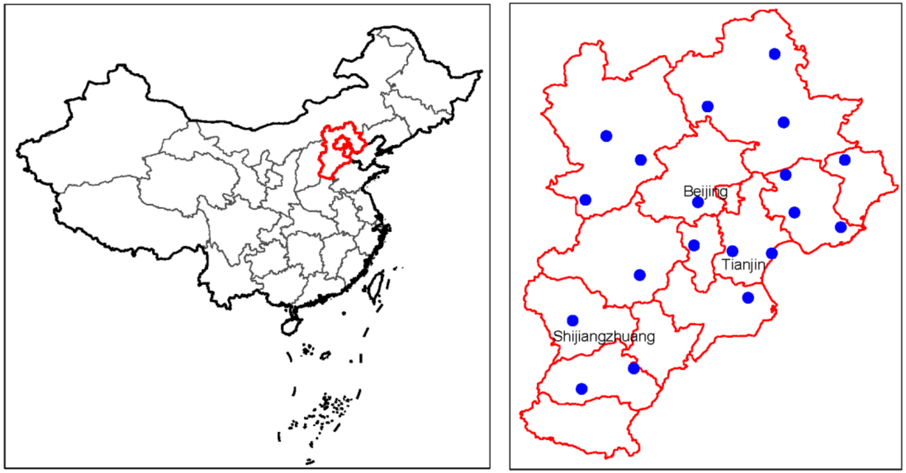


Figure 1. Research area and locations of the 19 synoptic meteorological stations.

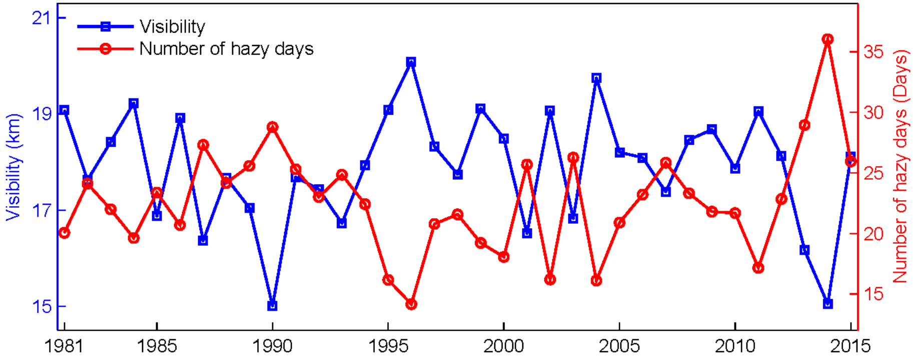
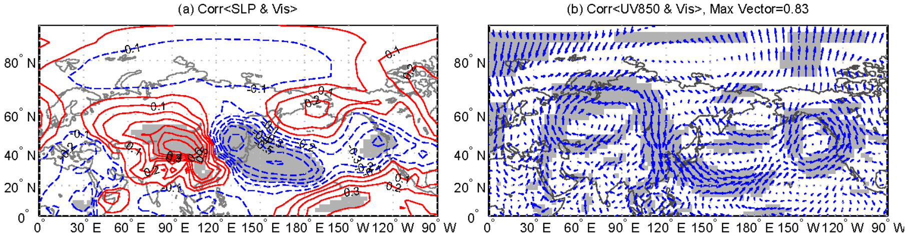
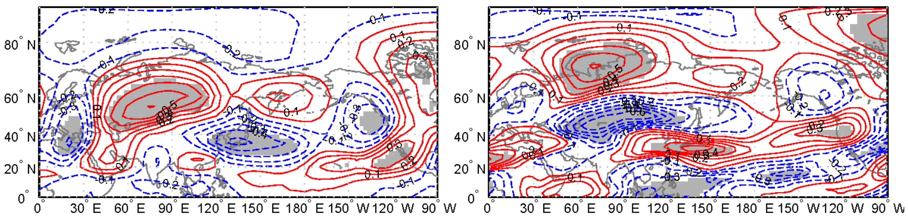


Figure 2. Curves of the winter mean visibility and number of hazy days in BTH.


(a) Corr<SLP & Vis>

(b) Corr<UV850 & Vis>, Max Vector=0.83


(c) Corr<H500 & Vis>

(d) Corr<U200 & Vis>

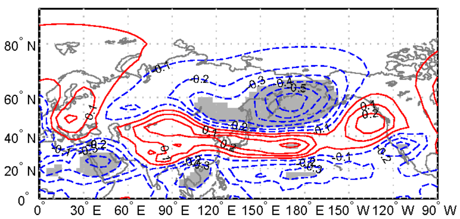

(e) Corr<airt200 & vis>

Figure 3. Spatial distribution of correlation coefficients between visibility and SLP **(a)**, UV850 **(b)**, H500 **(c)** and U200 **(d)** (area significant at the 0.05 level are shaded; either U850 or V850 significant at the 0.05 level are shaded in **b**).

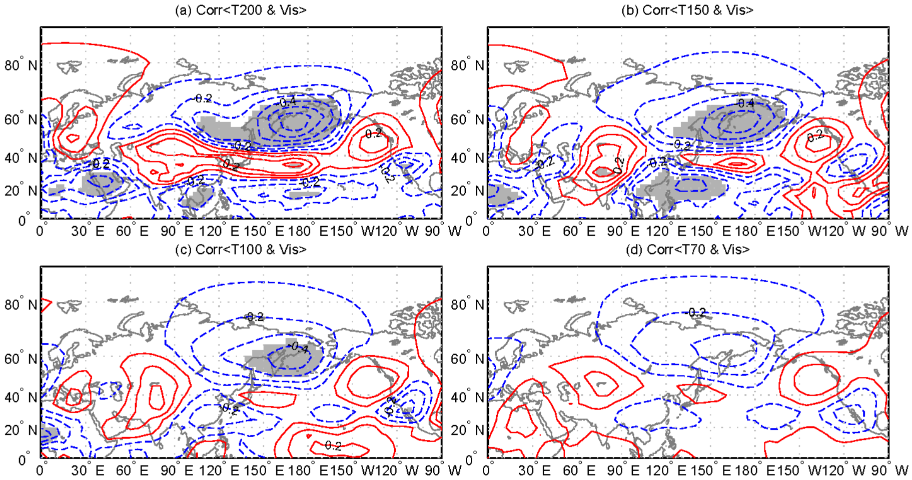


Figure 4. Spatial distribution of correlation coefficients between visibility and T200 **(a)**, T150 **(b)**, T100 **(c)** and T70 **(d)** (area significant at the 0.05 level are shaded).

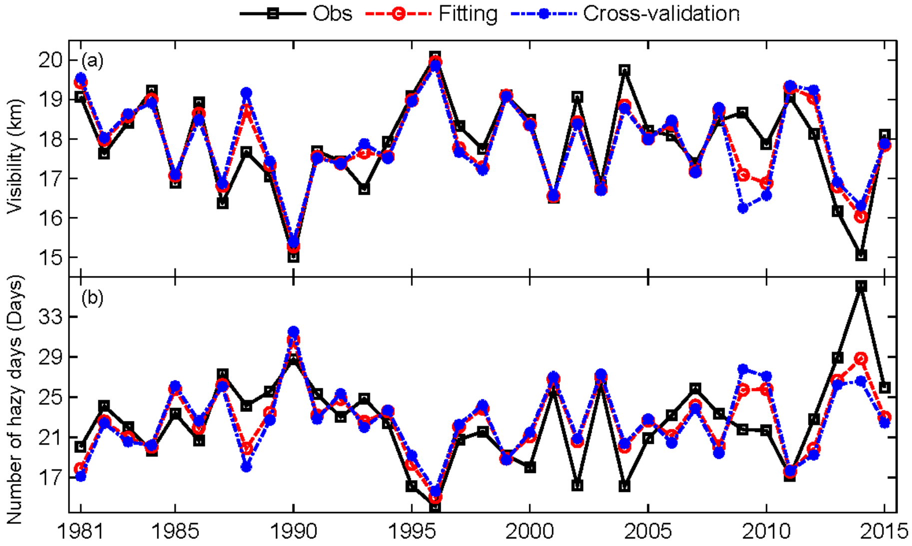
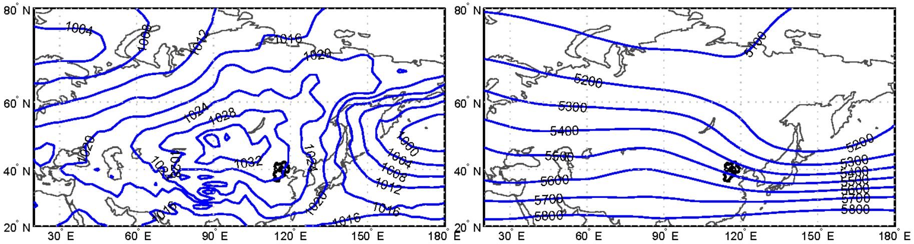
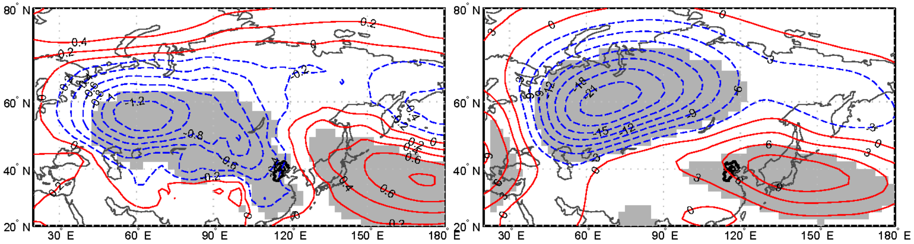


Figure 5. Curves of the observed and the predicted winter visibility **(a)** and number of hazy days **(b)** in the BTH region since 1981.



(a) Mean SLP in DJF (hPa) (b) Mean H500 in DJF (m)



(c) Reg<SLP & I_c> (d) Reg<h500 & I_c>

Figure 6. The climatological mean fields of SLP **(a)** and H500 **(b)** averaged in winter 1981 to 2010, and the spatial distribution of the regression coefficients of SLP **(c)** and H500 **(d)** upon the I_c over the period 1981 to 2015 (area significant at the 0.05 level are shaded).

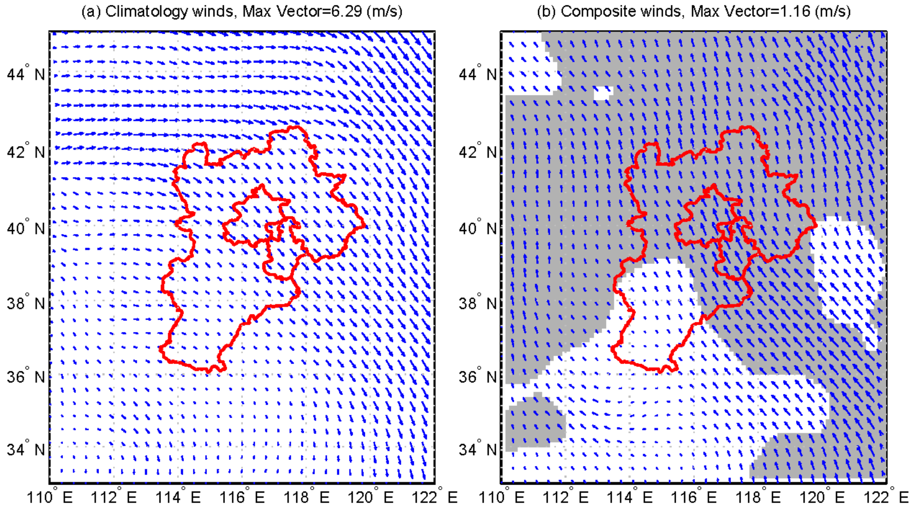
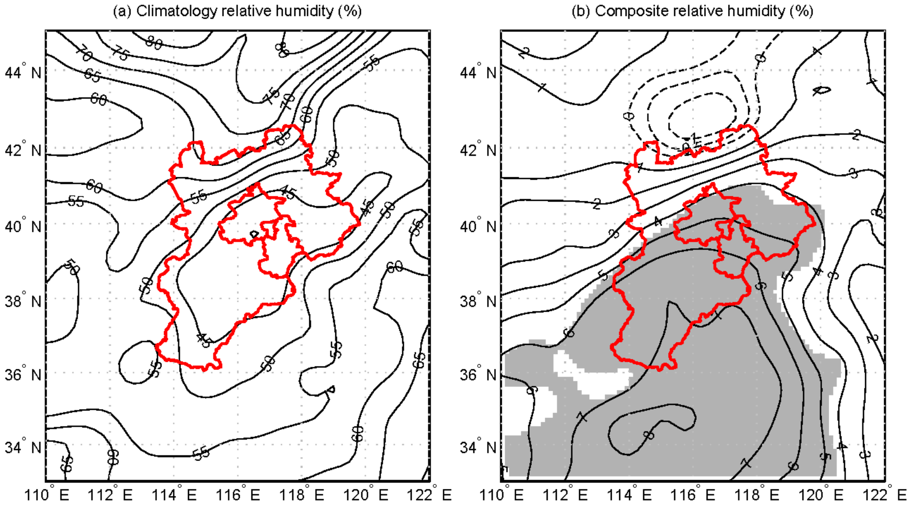


Figure 7. The climatological mean **(a)** and the composite **(b)** wind fields averaged from 1000 to 900 hPa (area significant at the 0.05 level are shaded).


(a) Climatology relative humidity (%)

(b) Composite relative humidity (%)

Figure 8. Same as Fig. 7, but for relative humidity.

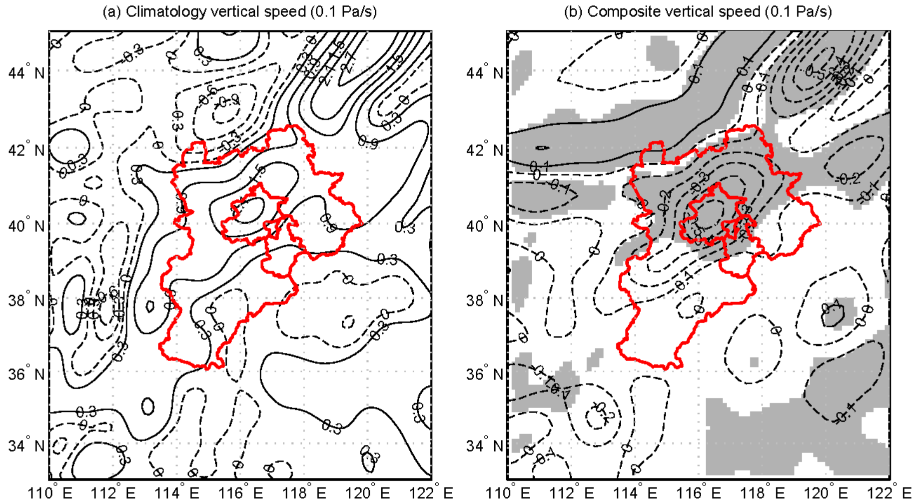


Figure 9. Same as Fig. 7, but for vertical speed.

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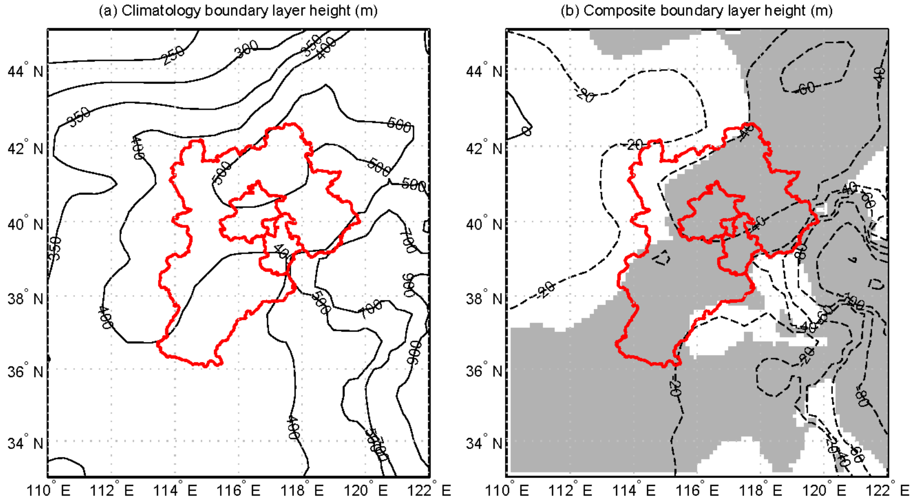

Figure 10. The climatological mean **(a)** and the composite **(b)** boundary layer height (area significant at the 0.05 level are shaded).

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