Analysis of the interannual variations and influencing factors of wind speed anomalies over the Beijing–Tianjin–Hebei region

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ABSTRACT
The wind field plays a decisive role in haze generation and dissipation processes over the Beijing–Tianjin–Hebei (BTH) region. Although geographically the BTH region is under the influence of the East Asian winter monsoon (EAWM), this study finds that common indices of the EAWM cannot adequately describe the actual wind speed changes in the BTH region. Thus, observational data are used to analyze the interannual variations of the winter wind field over the BTH region. The results show that the average winter wind speed is 2.0 m s\textsuperscript{-1}, with a slight rate of decline of 0.01 m s\textsuperscript{-1} yr\textsuperscript{-1}. In most cases, strong-wind years correspond to negative sea surface temperature (SST) anomalies over the tropical Pacific, whereas weak-wind years correspond to positive SST anomalies. Moreover, correlation and composite analyses show that the interannual variability is affected by multiple factors, including the following: (1) the pressure gradient in the high and middle latitudes of the Northern Hemisphere, as in strong-wind years the pressure gradient helps cold air move from high latitudes to middle latitudes; (2) the skin temperature in Eurasia, as low skin temperature in Eurasia in strong-wind years is conducive to the accumulation of cold air; and (3) the SST of the tropical Pacific east of the Philippines, as in strong-wind years the high temperature of this area affects the BTH region through anticyclonic activity and associated tropical circulation systems.

1. Introduction
The BTH region is located west of the Bohai Sea and north of the North China Plain (Figure 1(a)); its western and northern sides are close to the Taihang and Yanshan Mountains, respectively. Globally, this area has been one of the fastest developing areas over the last 30 years, as well as one of the most seriously air-polluted areas at the national level. In recent years, haze in the BTH region has become increasingly serious, especially in winter, seriously affecting public health and people’s daily lives. The causes of this haze, and potential measures to control it, have aroused widespread concern across the country. From the 1950s to the beginning of the twenty-first century, the average number of annual haze days in China has increased, and the increasing trend has been more obvious since the 1980s, especially in the BTH region (Gao 2014; Wu et al. 2010; Fu and Dan 2014). Haze is usually formed due to the interaction of a variety of air pollution sources. The pollution in Beijing originates not only from local pollutants but also from surrounding areas (Hebei, Tianjin, Tangshan, etc.) (Xu, Ding, and Bian 2006). Wind plays a decisive role in the regional transport of pollutants. Furthermore, changes in weather or climate conditions are also responsible for the increased haze, apart from the contribution from increased emissions of air pollutants. However, the dilution and diffusion capacity of pollutants in the atmosphere varies greatly due to different wind conditions (Wu 2011). In summary, the wind field over the BTH region plays a vital role not only in the regional transport of local contaminants, which determines the generation of the haze, but also in the dilution of the regional pollutants, which affects the dissipation of the haze.
2. Datasets

The following observational and reanalysis data are adopted in the present study:

1. Wind speed observational data from 154 national ground observation stations, with altitudes above sea level of less than 500 m (out of a total of 176 national ground observation stations in the BTH region). The original data are measurements of the daily average wind speed. The location of each site is shown in detail in Figure 1(b).

2. NCEP reanalysis 2 data (NCEP2) provided by the National Oceanic and Atmospheric Administration (NOAA), including zonal and meridional wind, mean sea level pressure (SLP), skin temperature (SKT), and 500-hPa geopotential height ($Z_{500}$), with monthly coverage from January 1979 to December 2015 and a spatial resolution of 2.5° latitude × 2.5° longitude.

3. Reanalysis data from the ERA-Interim data-set, including monthly zonal and meridional wind from January 1979 to December 2015 at a spatial resolution of 2.5° latitude × 2.5° longitude.

4. Extended Reconstructed Sea Surface Temperature (SST), version 3b (ERSST.v3b) data from NOAA, with monthly coverage from January 1979 to December 2015 at a spatial resolution of 2.0° latitude × 2.0° longitude.

5. SST data provided by NOAA for the Niño3.4 region, defined as the area-averaged SST over (5°N–5°S, 170°–120°W).

Moreover, the haze in this region shows an obvious characteristic of seasonal variation, with the number of haze days peaking in winter, decreasing in autumn and spring, and falling to their minimum levels in summer (Song et al. 2013; Fu and Dan 2014). In winter, the haze is directly related to the near-surface wind field, whereas in the other seasons it is influenced more by other factors (Liao et al. 2014). As a result, this study mainly investigates the factors influencing the interannual variation of the winter wind field over the BTH region.

The East Asian winter monsoon (EAWM) is widely known to be one of the most active circulation systems in the Northern Hemisphere during winter (Chen and Sun 1999; Huang, Zhou, and Chen 2003). Geographically, the BTH region falls under the influence of the EAWM. Thus, in this study, two EAWM indices are first analyzed to explore whether the winter wind field over the BTH region can be described by these common indices of the EAWM. Then, we focus on observational near-surface wind data recorded from 1978 to 2014, utilizing composite and correlation analyses to explore the main signal from the related atmospheric–oceanic physical fields affecting the interannual variation of the winter wind field over the BTH region.

Figure 1. Map of China showing the location of the Beijing–Tianjin–Hebei (BTH) region (black box). (b) Spatial distribution of the 154 observation stations in the BTH region.

Table 1. Correspondence between the years of anomalous wind fields ($V$) over the BTH (Beijing–Tianjin–Hebei) region and Niño3.4 SST anomalies.

| Year  | $V$  | Niño3.4 | Year  | $V$  | Niño3.4 |
|-------|------|---------|-------|------|---------|
| 1978  | 2.61 | −0.46   | 1988  | −1.62| −1.88   |
| 1979  | 1.02 | 0.21    | 1989  | −2.11| −0.05   |
| 1980  | 1.94 | −0.46   | 1990  | −1.21| 0.33    |
| 2003  | 1.42 | 0.43    | 1991  | −1.19| 1.71    |
| 2005  | 1.06 | −0.55   | 1992  | −1.34| 0.19    |
| 2008  | 1.22 | −0.61   | 1994  | −1.28| 1.04    |
| 2010  | 1.31 | −1.12   | 2002  | −1.06| 1.08    |
| 2014  | 1.08 | 0.84    |

Note: These are all standardized results.

In addition, two indices characterizing the strength of the EAWM, provided by the National Climate Center of the China Meteorological Administration, are also adopted; namely, the ‘EAWM intensity index’ and the ‘Siberian high intensity index’. The former is defined as the difference in air pressure between the sea (expressed as 160°E) and the
land (represented by 110°E) from 10° to 60°N, while the latter is defined as the average SLP in winter of the Siberian high (40°–60°N, 80°–120°E) (Guo 1994). The SST anomaly data of the Niño3.4 area, provided by NOAA, are also used to characterize the intensity of ENSO; the data comprise the anomalies of monthly average SST in the area (5°N–5°S, 170°–120°W).

To analyze the actual winter wind speed field over the BTH region, we focus on the available observational data. Without loss of generality, the average winter wind speed between 1981 and 2010 is set as the climate mean state. Then, the index of the winter wind field over the BTH region (the BTH index) is defined as the normalized time series of the average winter wind speed measured from the 154 observation stations over the BTH region after removing the climate mean state and linear trend. All years for which the BTH index is greater than 1 (the standard deviation of the BTH index) are referred to as strong-wind years, whereas all years for which the BTH index is less than –1 are referred to as weak-wind years (Table 1). According to the observational data, there are a total of eight strong-wind years (1978, 1979, 1980, 2003, 2005, 2008, 2010, and 2014) and seven weak-wind years (1988, 1989, 1990, 1991, 1992, 1994, and 2002).

### 3. Variability of the surface winds over the BTH region

First, the differences between the observational data and the reanalysis data, as well as the relationship between the observational data and the indices of the EAWM, are analyzed for the BTH region. Figure 2(a) compares the original time series from the observational data and the reanalysis data, where the former represents the average of the observations from 154 stations in the BTH region and the latter represents the regional mean wind speed over the BTH region (35°–42.5°N, 112.5°–120°E). Figure 2(b) shows the normalized and detrended version of the three time series from Figure 2(a). Figure 2(c) compares the observational data with the EAWM indices (EAWM intensity index and Siberian high intensity index). The average wind speed calculated from the observational data over the 37 years is 2.0 m s⁻¹, whereas the wind speeds calculated from ERA-Interim and NCEP2 are 2.1 m s⁻¹ and 3.0 m s⁻¹, respectively (Figure 2(a)). Moreover, whereas the observational data show that the rate of decrease in the wind speed is 0.01 m s⁻¹ yr⁻¹, ERA-Interim and NCEP2 data show a decrease by only 0.001 m s⁻¹ yr⁻¹. Furthermore, a comparison of the standardized and detrended time series (Figure 2(b)) shows that the pattern of interannual variation from the observational data is in good agreement with those of ERA-Interim NCEP2. Specifically, the correlation coefficients, for comparison between the observational and ERA-Interim data and the observational and NCEP2 data, are 0.58 and 0.39, respectively, and both exceed the 95% confidence level. As shown in Figure 2(c), there is no weakening trend for the two EAWM indices, as there is for the BTH index. Furthermore, after removal of the trend effects for the three indices, the correlation coefficient between the detrended BTH and Siberian high indices is 0.03, whereas the coefficient between the detrended BTH and EAWM indices is –0.01; neither value passes the reliability test. In summary, the common indices of the EAWM do not reflect the interannual variability or declining trend of the winter wind field over the BTH region. The observational data are therefore more suitable for exploring the interannual variations and influencing factors of winter wind speed anomalies over the BTH region.

ENSO, being the strongest signal in oceanic-atmospheric interactions, has a significant influence on the global interannual variability of atmospheric circulation. To analyze the factors influencing winter wind speed anomalies over the BTH region, the relationship between anomalous winter wind speeds over the BTH
the eight strong-wind years, the east-central part of the tropical Pacific shows negative SST anomalies, whereas in five out of the seven weak-wind years it shows positive SST anomalies over the central and eastern Pacific near the equator are analyzed using the BTH and Niño3.4 indices. As shown in Table 1, in five out of the eight strong-wind years, the east-central part of the tropical Pacific shows negative SST anomalies, whereas in five out of the seven weak-wind years it shows positive SST anomalies.

Figure 3. Correlation of the BTH (Beijing–Tianjin–Hebei) index with the (a) SLP, (b) Z500 (500-hPa geopotential height), (c) SKT (skin temperature), and (d) SST, in the winters (December to the following February) of 1978–2014. Notes: The climatology (1981–2010) and linear trend have been removed for each physical field. Dotted areas are statistically significant at the greater than 95% confidence level, according to the Student’s t-test.

Figure 4. Composite analysis of the BTH (Beijing–Tianjin–Hebei) index and the (a) SLP, (b) Z500 (500-hPa geopotential height), (c) SKT (skin temperature), and (d) SST, in the winters (December to the following February) of the eight strong-wind years.
latitudes. Finally, the correlation analysis for SST (Figure 3(d)) shows significant positive correlation in the tropical Pacific, east of the Philippines. Previous studies have demonstrated that, during El Niño periods, there are negative SST anomalies east of the Philippines in the western Pacific accompanied by anomalous anticyclonic activity, which brings southerly wind anomalies in the northwest of these anticyclones, and weakens the winter monsoon along the East Asian coast (Wang, Wu, and Fu 2000; Zhang, Li, and Jiang 2012). This coincides with the results in Table 1 insofar as, in El Niño years, the SST anomalies around the Philippine Sea area are relatively cold, and weak winds occur in the BTH region; whereas, in La Niña years, the SST anomalies around the Philippines region are warm, and strong winds occur in the BTH region. In terms of circulation, the positive correlation in the high latitudes of the BTH region and local negative correlation centers form a north–south air pressure gradient that facilitates the movement of cold air from the high latitudes to the middle latitudes, thus affecting the wind anomalies over the BTH region. From the perspective of the temperature field, the interannual variation of the wind field over the BTH region is closely related to the SKTs of the mid- and high-latitude regions — essentially the Eurasian continental land mass. Through atmospheric circulation, the surface temperature affects the wind field over the BTH region (Wu et al. 2016). At the same time, the interannual variation is also directly affected by the tropical Pacific temperature through the effects of anticyclones and associated tropical SST anomalies. Therefore, the winter wind field over the BTH region also has a corresponding relationship with the SST in the east-central part of the tropical Pacific: strong-wind years correspond to negative SST anomalies, whereas weak-wind years correspond to positive SST anomalies.

To determine the influences of various factors on the winter wind field over the BTH region, we calculate the correlation between the BTH index and the global SLP, SKT, Z500, and SST fields for the winters of 1978–2014, with the climatology (1981–2010) and linear trend removed for each physical field (Figure 3). Based on the correlation analysis for SLP shown in Figure 3(a), it is apparent that there is a large positive correlation area in the high-latitude area around the Arctic region. Meanwhile, in the midlatitude area, there are three significant negative correlation centers, located in East Asia, the subtropical Atlantic and Europe, and North Africa. In addition, the correlation analysis for Z500 (Figure 3(b)) shows that there are abnormal rise and sink areas corresponding to the areas shown in Figure 3(a). Specifically, there is a positive correlation in the high-latitude area around the Arctic, meaning that there are sinking air flows in strong-wind years; while there is negative correlation in midlatitude East Asia, the subtropical Atlantic and Europe, and North Africa, implying there are rising air flows in weak-wind years. Furthermore, the correlation analysis for SKT (Figure 3(c)) shows that there is negative correlation in Eurasia, indicating that, in strong-wind years, the SKT in this area is low, which favors the accumulation/propagation of cold air in/to the low latitudes. Finally, the correlation analysis for SST (Figure 3(d)) shows significant positive correlation in the tropical Pacific, east of the Philippines. Previous studies have demonstrated that, during El Niño periods, there are negative SST anomalies east of the Philippines in the western Pacific accompanied by anomalous anticyclonic activity, which brings southerly wind anomalies in the northwest of these anticyclones, and weakens the winter monsoon along the East Asian coast (Wang, Wu, and Fu 2000; Zhang, Li, and Jiang 2012). This coincides with the results in Table 1 insofar as, in El Niño years, the SST anomalies around the Philippine Sea area are relatively cold, and weak winds occur in the BTH region; whereas, in La Niña years, the SST anomalies around the Philippines region are warm, and strong winds occur in the BTH region. In terms of circulation, the positive correlation in the high latitudes of the BTH region and local negative correlation centers form a north–south air pressure gradient that facilitates the movement of cold air from the high latitudes to the middle latitudes, thus affecting the wind anomalies over the BTH region. From the perspective of the temperature field, the interannual variation of the wind field over the BTH region is closely related to the SKTs of the mid- and high-latitude regions — essentially the Eurasian continental land mass. Through atmospheric circulation, the surface temperature affects the wind field over the BTH region (Wu et al. 2016). At the same time, the interannual variation is also directly affected by the tropical Pacific temperature through the effects of anticyclones and associated tropical

Figure 5. Composite analysis of the BTH (Beijing–Tianjin–Hebei) index and the (a) SLP, (b) Z500 (500-hPa geopotential height), (c) SKT (skin temperature), and (d) SST, in the winters (December to the following February) of the seven weak-wind years.
circulation systems that affect the BTH region. In summary, the interannual variability of the wind field over the BTH region is the result of a multi-factor response — specifically, the interaction of the mid–high latitudes and the tropical circulation.

A composite analysis of the anomalous distribution of related atmospheric–oceanic physical fields in the strong-wind years (Figure 4) and weak-wind years (Figure 5) is conducted, including SLP, SKT, and Z500 from NCEP2 and ERSST v3b, with the mean state (for 1981–2010) and linear trend removed for each physical field, based on the selected eight strong-wind and seven weak-wind years indicated in Table 1. From the anomaly field of the SLP synthesized from strong-wind years (Figure 4(a)) and the anomaly field of the Z500 (Figure 4(b)), it is apparent that there are three negative-value centers in the Northern Hemisphere: in the midlatitudes of East Asia, south of Baikal Lake; on the eastern coast of the United States; and in southern Europe. Meanwhile, located to the northeast of each of the aforementioned negative centers, there are positive centers, which are located in the Bering Sea, south of Iceland, and northwest of Russia. Based on the data synthesized from the weak-wind years (Figure 5(a) and (b)), it is apparent that the circulation fields in the strong-wind years and weak-wind years are oppositely distributed. From the analysis of the temperature field anomalies (Figures 4(c) and 5(c)), it is apparent that the temperature anomalies over the Eurasian continent show a north–south gradient. There is an anomalous SST signal on the western Pacific coast between 30°N and 30°S, which corresponds to warm sea temperature in strong-wind years and cold sea temperature in weak-wind years. In addition, it is clear from the SST anomaly field that the SST of the tropical Pacific area corresponds negatively in strong-wind years (Figure 4(d)) and positively in weak-wind years (Figure 5(d)). In general, the conclusions that may be drawn from the composite analysis are basically consistent with those based on the correlation analysis, i.e., that the interannual variation of the winter wind field over the BTH region is the result of multi-factor interactions. The composites not only show that the interannual variation is affected by the pressure gradient between the middle and high latitudes, the SKT in Eurasia, and the SST in the northwestern Pacific Ocean east of the Philippines, but also that the SST anomaly signal in the central and eastern part of the tropical Pacific is quite significant too.

4. Discussion and conclusion

In this study, near-surface winter wind field observational data are analyzed along with related atmospheric–oceanic physical fields from reanalysis data (the EAWM and Niño3.4 indices) to explore the variations in the winter wind field over the BTH region from 1978 to 2014 and the possible factors influencing the changes.

The results show that the winter wind field over the BTH region has a slight rate of decline of 0.01 m s⁻¹ yr⁻¹ and an average wind speed of 2.0 m s⁻¹ according to the observational data. Surprisingly, the commonly used index of the EAWM does not adequately describe the winter wind field characteristics over the BTH region, either in terms of its interannual variability or its declining trend. However, we find that, in most cases, strong-wind years correspond to negative SST anomalies over the tropical Pacific, while weak-wind years correspond to positive SST anomalies.

Correlation analysis shows that the interannual variation of the winter wind field over the BTH region is related to multiple factors. In terms of circulation, the interannual variation is affected by the pressure gradient between the middle and high latitudes. Specifically, the positive correlation in the upper reaches of the BTH region and local negative correlation centers form a north–south air pressure gradient that helps cold air move from the high latitudes to the midlatitudes in strong-wind years, thus affecting the winter wind anomalies over the BTH region. From the perspective of the temperature field, the SKT of the Eurasian continent is also a factor of influence for the interannual variation of the winter wind field over the BTH region. Through atmospheric circulation, the SKT impacts changes in the winter wind field over the BTH region. The interannual variation is also directly affected by the SST of the northwestern Pacific through anticyclones and associated tropical circulation systems that affect the BTH region. In general, the conclusions drawn from the composite analysis are basically consistent with those based on the correlation analysis. Finally, the results also indicate that the SST anomaly signal in the east-central part of the tropical Pacific is also quite significant.

The conclusions of this paper are relatively preliminary; further in-depth research and validation using additional data and climate system models are required to study the impacts and relative importance of various factors on the wind field over the BTH region.

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