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Possible Influence of the Antarctic Oscillation on Haze Pollution in North China

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Key Points:
- Haze pollution in North China is significantly correlated with the preceding AAO
- The responses of local and regional meteorological conditions to the AAO lend support to the findings
- The southern Indian Ocean may exert an important influence on the link between haze pollution and the AAO through two possible pathways

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Abstract In this study, the possible influence of the Antarctic oscillation (AAO) on winter haze pollution (indicated by atmospheric visibility after rain, fog, dust, snowstorms, etc. are removed) in North China (NC) was investigated. The results show that the mean winter visibility (December-January-February visibility) throughout most of eastern China is negatively correlated with the preceding AAO (August-September-October (ASO)-AAO), especially in NC. The interannual correlation coefficient between DJF-VIS in NC and the ASO-AAO is −0.52, which is significant at the 99% level. The negative correlation suggests that an enhancing (weakening) ASO-AAO could be conducive to increases (decreases) of haze pollution in NC in boreal winter. The responses of local and regional meteorological conditions to the ASO-AAO support the relationship between the ASO-AAO and winter air pollution in NC. A preliminary mechanism analysis shows that a positive ASO-AAO may induce a sea surface temperature warming tendency in the Northwestern Southern Indian Ocean. This warming then causes a wave train-like pattern in the upper troposphere along the jet stream and an anomalous zonal cell that weakens the regional Hadley circulation from the Maritime continents to East Asia. All of these factors are favorable to the formation of anomalous southerly and haze pollution in NC.

1. Introduction

East China (EC) has suffered from severe haze or smog days frequently in recent years. These events are characterized by high particle mass concentrations and low visibility. Severe haze pollution, especially persistent haze days (i.e., in January 2013 and November to December 2015), has greatly threatened human health and traffic safety (Sun et al., 2016; Tao et al., 2014; Zhang et al., 2017). In past few years, studies performed to explore the cause of haze pollution in EC have found that there are three main causes of haze pollution. First, pollutant emissions in the lower atmosphere from fossil fuel combustion, construction, and other sources due to rapid economic development and urbanization are the most essential and internal reasons (Tie et al., 2015; Wu et al., 2011). Second, meteorological conditions strongly influence haze pollution through the accumulation or diffusion, spread, and regional transport of air pollutants as well as the formation of secondary aerosols, which are generated by complicated physical and chemical reactions (Jeong & Park, 2013; Li et al., 2017; Marais et al., 2016; Ramsey et al., 2014; Wang et al., 2010; Yin & Wang, 2017; Zhang et al., 2014; Zheng et al., 2015). Third, topography influences haze pollution that occurs in Beijing and eastern China (Xu et al., 2015; Zhang et al., 2018).

In view of the invariable terrain conditions and unchanging (or slowly changing) pollutant emissions over short periods, the occurrence and degree of haze pollution are primarily determined by meteorological conditions of both synoptic, monthly to seasonal and interannual timescales (Li, Zhang, et al., 2016; Mues et al., 2012; Whiteaker et al., 2002; Zhang et al., 2015). Zhang et al. (2016) suggested that a close relationship exists between winter haze pollution in the Beijing-Tianjin-Hebei region and the atmospheric circulation at middle-high latitudes over a long-term perspective from 1980 to 2015. Other studies have suggested that the haze pollution across central and eastern China is closely related to the East Asian winter monsoons and the relevant climate factors (Cao et al., 2015; Chen & Wang, 2015; Cheng et al., 2016; Hien et al., 2011; Li, Lau, et al., 2016; Li, Zhang, et al., 2016; Wang & Chen, 2016; Wu et al., 2016; Yin et al., 2017).

These previous studies were mainly confined to examining the influence from meteorology or climate factors in the Northern Hemisphere on haze pollution in EC. Thus, we wondered whether atmospheric activity in the Southern Hemisphere influences air pollution in China. Some studies have demonstrated the frequent interactions between the Northern and Southern Hemispheres via the atmosphere (Jones et al., 2018; Lu & Guan, 2009). The Antarctic oscillation (AAO; which was multiplied by −1 throughout the study to simplify understanding), also known as the southern annular mode, is the dominant mode of extratropical atmospheric circulation in the Southern Hemisphere and is characterized by zonal symmetry (Abram et al., 2014; Gong & Wang, 1999; Thompson & Wallace, 2000; Wu et al., 2009). The AAO not only plays important roles in large-scale and regional climate changes over the Southern Hemisphere (Fogt et al., 2017; Jones et al., 2016; Lovenduski & Gruber, 2005; Mao et al., 2013; Reason & Rouault, 2005) but also exerts notable influences on climate anomalies in East Asia, especially on precipitation (Nan & Li, 2003; Wang & Fan, 2005) and dust storms (Fan & Wang, 2004; Lang, 2008) in China. However, no studies have focused on the possible effects of the AAO on the serious haze events or air pollution in North China (NC). Thus, the main purposes of this study are to examine the relationship between the AAO and winter haze pollution in NC and to investigate the possible physical mechanism of such an influence. This knowledge could be useful for predicting winter haze pollution and could provide scientific support for advance government actions to effectively reduce or control the pollutant emission when an anomalous AAO occurs that could lead to serious haze pollution in the region. This paper is organized as follows. Section 2 describes the data and methods used. The major results and discussions are presented in sections 3 and 4, respectively. Finally, we summarize our conclusions in section 5.

2. Data and Methods

Due to a lack of long-term instrumental records for air pollutant concentration, evolution of air pollution events and their relations with atmospheric circulations are not well understood. In this study, we intend to use atmospheric visibility data derived from synoptic meteorological stations to describe the evolution of haze pollution in EC since the 1980s. Many studies have demonstrated that in the absence of certain weather conditions (e.g., rain, fog, dust, and snowstorms), visibility is an excellent indicator of air quality because it degrades due to light scattering and absorption by atmospheric particles and gases, which originate from either natural or anthropogenic sources (Baddock et al., 2014; Baumer et al., 2008; Chang et al., 2009; Sabetghadam et al., 2012), although overall visibility is determined by airborne pollutants and meteorological parameters such as relative humidity, wind speed, temperature, pressure, and solar radiation (Deng et al., 2014; Wen & Yeh, 2010). In the present study, records of visibility and other meteorological variables (i.e., relative humidity, wind speed, and wind direction) at 14:00 PM (Beijing time) around the Chinese mainland since 1980 derived from the China Meteorological Administration were collected. We first removed visibility records accompanied by the weather phenomena of rain, fog, dust, and snowstorms. Subsequently, the stations with a missing data rate (the number of days without valid visibility records divided by the total days of each winter) of more than 30% were further excluded. Finally, we used the visibility records from 542 synoptic meteorological stations around China to indicate haze pollution in this study. Moreover, the monthly ERA-Interim reanalysis data with a spatial resolution of $0.75° \times 0.75°$ (Dee et al., 2011) and the monthly sea surface temperatures (ERSSTv5; Huang et al., 2017) were also included.

The monthly AAO index is defined as the difference in the normalized monthly zonal-mean sea level pressure between 40°S and 70°S (Nan & Li, 2003) and is a modification of the AAO index defined by Gong and Wang (1999). However, due to the higher spatial resolution of the ERA-Interim reanalysis data, we used the averages of 41–39°S and 71–69°S instead 40°S and 70°S, respectively. The correlation coefficient between the monthly AAO index used in the study and the monthly AAO index derived from the Climate Prediction Center of the National Centers for Environmental Prediction for January 1979 to December 2017 is 0.92, which is significant at the 99% level ($p > 99\%$). For simplicity, the AAO index was multiplied by −1 throughout this study.

Commonly used statistical methods, such as composite analyses and Pearson correlation analyses with a two-tailed Student's t test, were employed in this research. Moreover, to reduce the possible effects of low-frequency variations or long-term trends and to examine whether the correspondence between these two time series is stable on an interannual timescale, the high-frequency (<10 yr) correlation of the high-pass-

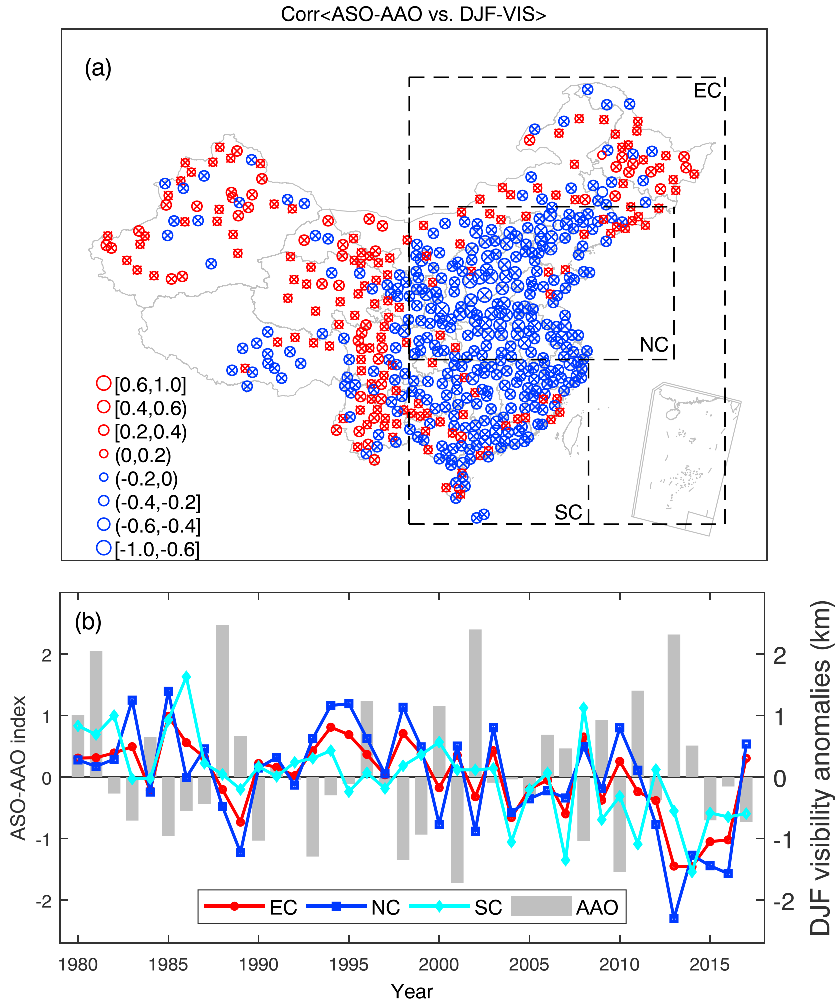

Figure 1. Spatial distribution of high-frequency (<10 yr) correlation coefficients between the AAO index in ASO (ASO-AAO) and the mean visibility in boreal winter (DJF-VIS) in China and the original curves of (a) DJF visibility anomalies in East China (EC), North China (NC), and South China (SC) and (b) the ASO-AAO index (the crosses denote significance at the 95% level in Figure 1a; the years labeled on the *x*-axis are based on the ASO-AAO; thus, 1 year should be added to these values when considering the DJF visibility series in Figure 1b.) AAO = Antarctic oscillation; ASO = August-September-October; DJF-VIS = December-January-February visibility.

filtered time series was also tested by using the Butterworth filter (Gong & Luterbacher, 2008; Zhang et al., 2016). This method can ensure that the effective degree of freedom of correlation coefficient does not decrease significantly. In fact, it is very close to N (number of samples) − 2. Moreover, it should be noted that the boreal winter of 1981 consists of December 1980 and January and February 1981.

3. Results

3.1. Influence of the AAO on Boreal Winter Air Pollution in NC

We first examined the spatial distribution of original (unfiltered) and high-frequency (<10 yr) correlation coefficients between the 3-month moving AAO indices from March-April-May (MAM, 10 months in advance) to the boreal winter December-January-February (DJF) and the mean visibilities at 542 synoptic meteorological stations around China. Intuitively, the August-September-October (ASO) AAO was most significantly correlated with winter visibility in NC (east of 105°E and between 30°N and 43°N on the Chinese mainland; Figure 1a and Table 1). In the original correlations ($r1$), the maximum correlations occurred between the ASO-AAO and DJF visibility (DJF-VIS) in both EC (east of 105°E; −0.44) and NC (−0.50), respectively. Both are significant at the 95% level. Furthermore, most of the high-frequency correlations

Table 1
Correlation Coefficients Between the Leading AAO Index and DJF Visibility in EC, NC and SC

		MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
EC	$r1$	0.17	0.19	0.19	−0.01	−0.24	−0.44**	−0.34**	−0.29*	−0.20	0.01
	$r2$	0.07	0.02	−0.02	−0.26*	−0.41**	−0.50**	−0.40**	−0.37**	−0.17	0.00
NC	$r1$	0.08	0.12	0.13	−0.05	−0.26*	−0.50**	−0.39**	−0.39**	−0.30*	−0.10
	$r2$	−0.01	−0.05	−0.07	−0.28*	−0.39**	−0.52**	−0.42**	−0.48**	−0.28*	−0.12
SC	$r1$	0.29*	0.26*	0.20	−0.01	−0.12	−0.17	−0.14	0.00	0.12	0.29*
	$r2$	0.12	0.08	−0.01	−0.19	−0.29*	−0.27*	−0.21	0.01	0.09	0.19

Note. $r1$ and $r2$ indicate the raw correlation and high-frequency (<10 yr) correlation, respectively; MAM denotes the mean of March, April, and May; AMJ denotes the mean of April, May, and June, and so on. EC = East China; NC = North China; SC = South China.
*Significant at the 90% level based on a two-tailed Student's t test. **Significant at the 95% level.

are larger than the original correlations. For example, the high-frequency correlations ($r2$) between the ASO-AAO and DJF-VIS in EC and NC reach 0.50 and 0.52, respectively. This suggests that the links between the winter visibility changes in EC and ASO-AAO activities remain stable from year to year, especially in NC. The temporal variabilities of the mean winter visibility in EC and NC are generally consistent with the annual ASO-AAO index (Figure 1b). For example, the minimum NC visibility in the winter of 2013/2014 corresponded to a maximum AAO in ASO 2013, and the reduced haze pollution occurring in NC in the winter of 2017/2018 corresponded well to a negative ASO-AAO in 2017. The significantly negative correlations suggest that the negative (positive) AAO in the ASO season is associated with the increase (decrease) of visibility (viz., the improvement or deterioration of air quality or air pollution) in NC in boreal winter. Additionally, negative correlations also occurred in South China (SC; east of 105°E and south of 30°N), although the correlation coefficients are distinctly weaker than that in EC and NC. The original and high-frequency correlations between the ASO-AAO and DJF-VIS in SC are −0.17 and −0.27 (p > 99%), respectively. Therefore, we will focus on the relationships between the AAO and haze in NC and the possible causes in this study.

The relationship between the ASO-AAO and winter visibility in NC is obvious, but how does AAO variability affect the winter air pollution in NC? As mentioned in section 1, haze pollution events in Beijing or eastern China are closely related to anomalous local and large-scale meteorological conditions. In particular, they are directly related to the wind speed and relative humidity conditions (Zhang et al., 2015; Zhang et al., 2016). Based on the daily records from synoptic meteorological stations, the possible relationships of surface wind and relative humidity in boreal winter to the ASO-AAO were examined (Figure 2). To reduce the possible effects of low-frequency variation or long-term trends and to examine whether the response is stable on an interannual timescale, all the time series were high-pass filtered before the correlation analyses were conducted. The vectors in Figure 2a denote the high-frequency correlation coefficients between the ASO-AAO and the surface meridional (V10, calculated from the wind speed and wind direction records by a trig function) and zonal (U10, same as V10) winds in boreal winter. The upward and eastward directions indicate positive correlations. Figure 2a shows that anomalous southeasterly winds dominate in NC; namely, negative (positive) correlations between the ASO-AAO and U10 (V10) winds occur at most NC meteorological stations. Specifically, the original (high-frequency) correlation coefficients between the ASO-AAO and the mean winter U10 and V10 and the surface wind speeds (W10, viz., the square root of $U10^2 + V10^2$) in NC are −0.58 (−0.55; $p > 99\%$), 0.25 (0.23; close to the 90% confidence level), and −0.52 (−0.50; $p > 99\%$). These significant correlations suggest that the negative (positive) ASO-AAO cause stronger (weaker) northwest winds in NC areas than the climatological surface winds. In contrast to wind speed, ASO-AAO is significantly positively correlated with the relative humidity of most NC stations (Figure 2b). The original and high-frequency correlation coefficients between the ASO-AAO and the mean winter relative humidity in NC are 0.36 ($p > 95\%$) and 0.46 ($p > 99\%$), respectively. These positive correlations suggest that an increase (reduction) of the winter relative humidity in NC generally corresponds to a positive (negative) ASO-AAO. A strengthening (weakening) northwesterly wind and low (high) relative humidity are (not) conducive to the spread and elimination of air pollutants. Then, the reduction (increase) in pollutant concentrations will certainly improve (depress) the visibility in boreal winter in NC areas. The responses of the local meteorological conditions to ASO-AAO well support the findings of the influence of ASO-AAO on the winter haze pollution in NC.

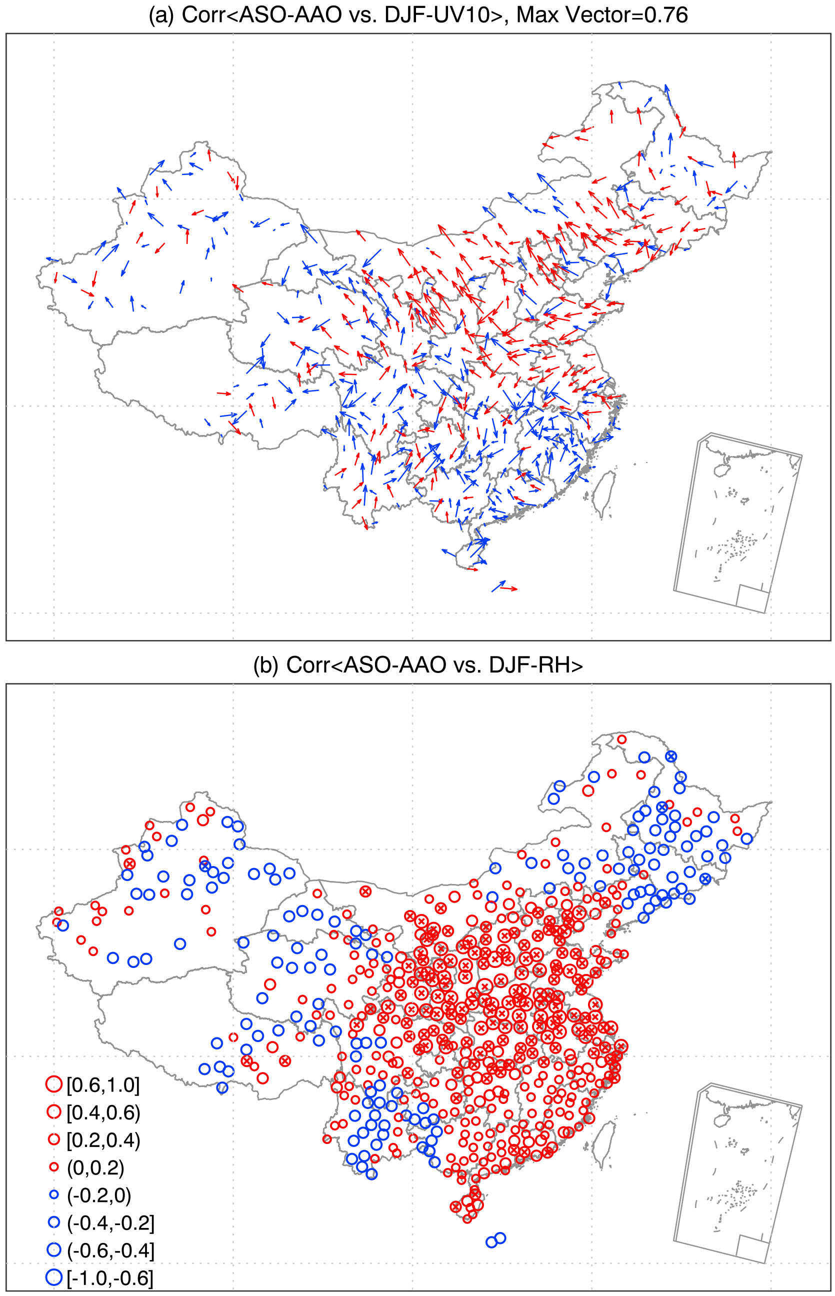

Figure 2. Spatial distribution of high-frequency correlation coefficients between the (a) ASO-AAO and surface winds in boreal winter (DJF-UV10) and (b) relative humidity (DJF-RH; if either U10 or V10 is significant at the 95% level, then the vectors are shaded in red in Figure 2a; the crosses denote significance at the 95% level in Figure 2b). AAO = Antarctic oscillation; ASO = August-September-October; DJF = December-January-February.

Furthermore, we examined the correlations between large-scale anomalous circulations, such as zonal and meridional winds at 850 hPa (UV850) and 200 hPa (UV200) in boreal winter, and the ASO-AAO. In UV850, an anomalous anticyclonic circulation occurred from northern China to the northwestern Pacific, and anomalous southeasterly winds dominated in NC (Figure 3a). Based on the climatological horizontal wind fields at the middle-low troposphere (figures omitted), the anomalous southeasterly winds in NC suggest that the northwesterly winds from high latitude to northern China tend to be weaker (stronger) in a positive (negative) ASO-AAO. The responses of the lower tropospheric wind fields to ASO-AAO are likely connected to upper troposphere responses. In UV200, an anomalous anticyclonic circulation also exists in northern

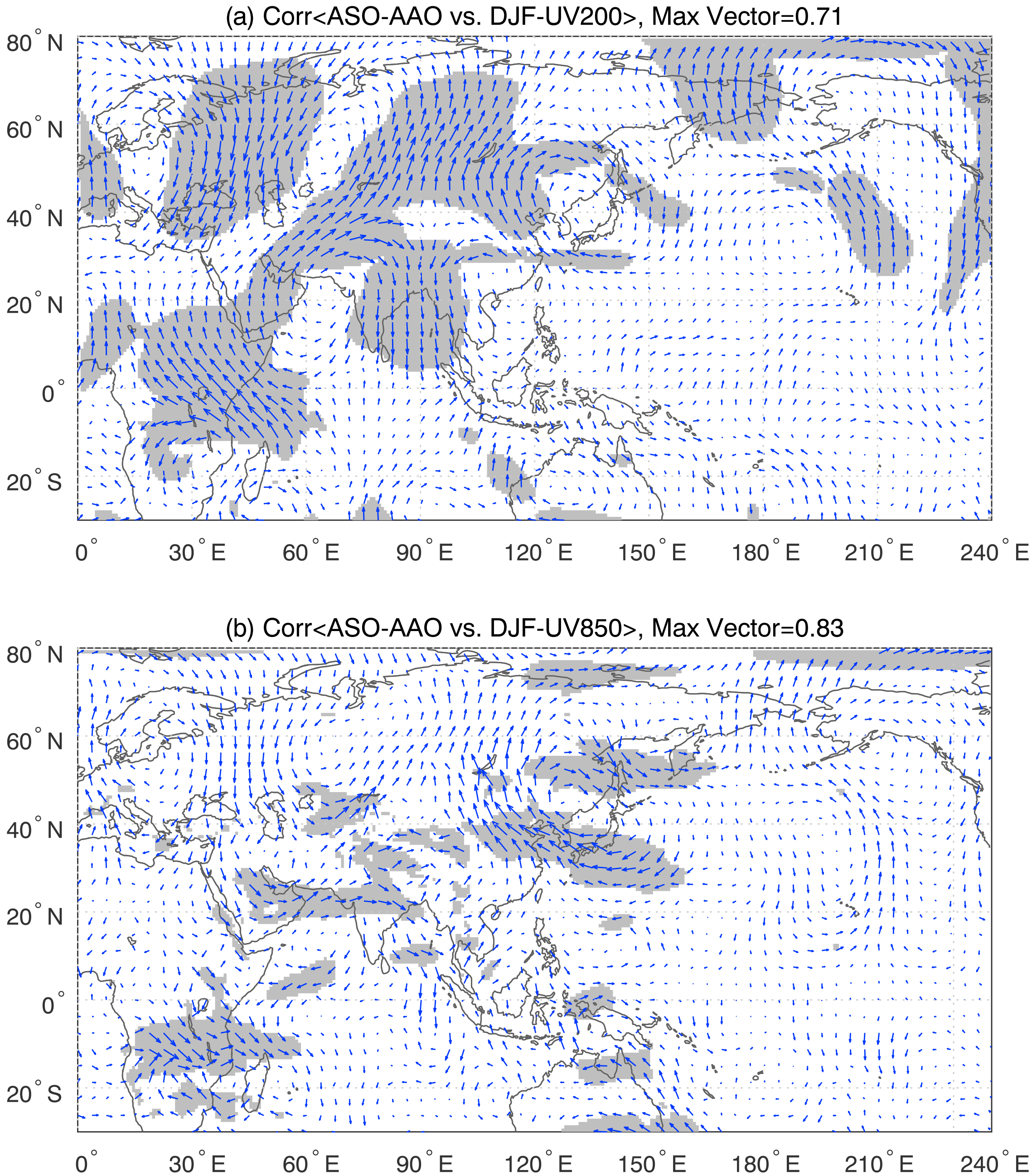

Figure 3. Spatial distribution of high-frequency correlation coefficients between the ASO-AAO and zonal and meridional winds at (a) 200 hPa and (b) 850 hPa (if either the zonal or meridional component are significant at the 90% level, then the vectors are shaded in gray). AAO = Antarctic oscillation; ASO = August-September-October; DJF = December-January-February.

China (Figure 3b). This pattern implies that in the positive phase of the ASO-AAO, the south (north) of the East Asian jet stream weakened (strengthened), coinciding with the anomalous sinking (ascending) motions that occurred in the south (north) of the Jet stream entrance in the upper troposphere, which led to the weakening northerly winds that appeared in the lower troposphere. Generally, all the response patterns from the lower to upper troposphere show an anomalous quasi-barotropic structure, which suggests that a positive (negative) ASO-AAO might induce a weakening (enhancing) of the East Asian winter monsoon. The weakened (strengthened) northerly winds lead to increased (decreased) air pollutant concentrations and decreased (increased) visibility in eastern China, especially in NC areas.

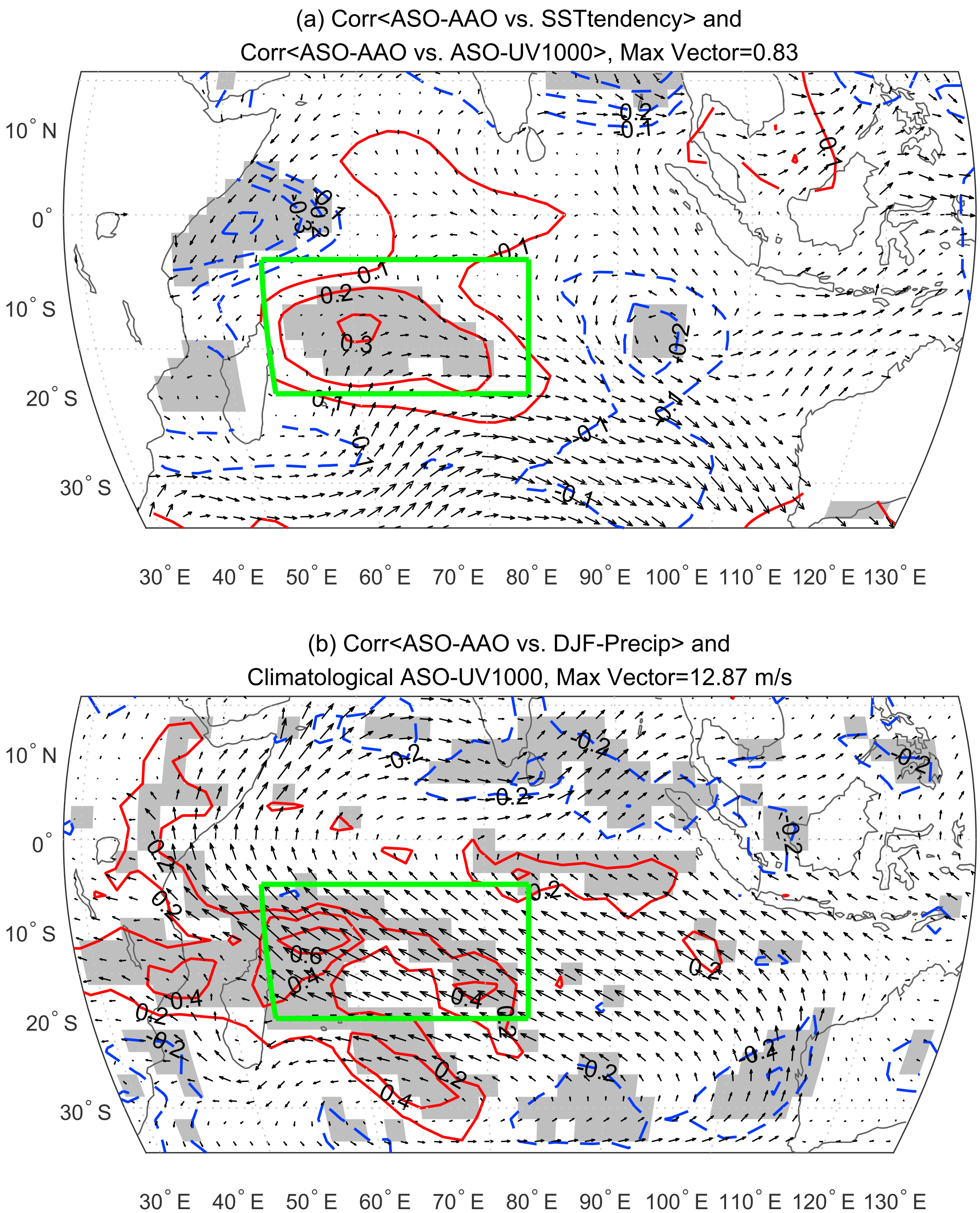

Figure 4. Spatial distribution of high-frequency correlation coefficients between (a) ASO-AAO and the tendency of SSTa (DJF-SSTa minus ASO-SSTa) and zonal and meridional winds at 1,000 hPa and (b) precipitation during DJF (the correlation coefficients between ASO-AAO and SSTtendency and precipitation that tend to be significant at or near the 90% level are indicated by gray shading). AAO = Antarctic oscillation; ASO = August-September-October; DJF = December-January-February; SSTa = sea surface temperature anomalies; SSTtendency = sea surface temperature tendency.

3.2. Mechanism for the Influence of the Preceding AAO on Winter Haze Pollution

The responses of the local and regional atmospheric circulations to the ASO-AAO confirmed that the ASO-AAO plays a role in winter haze pollution in NC. However, what is in question is the specific influence mechanisms of the preceding activity of the ASO-AAO on winter haze pollution in NC. In other words, how are the anomalous signals of the ASO-AAO remembered and transmitted to the boreal winter

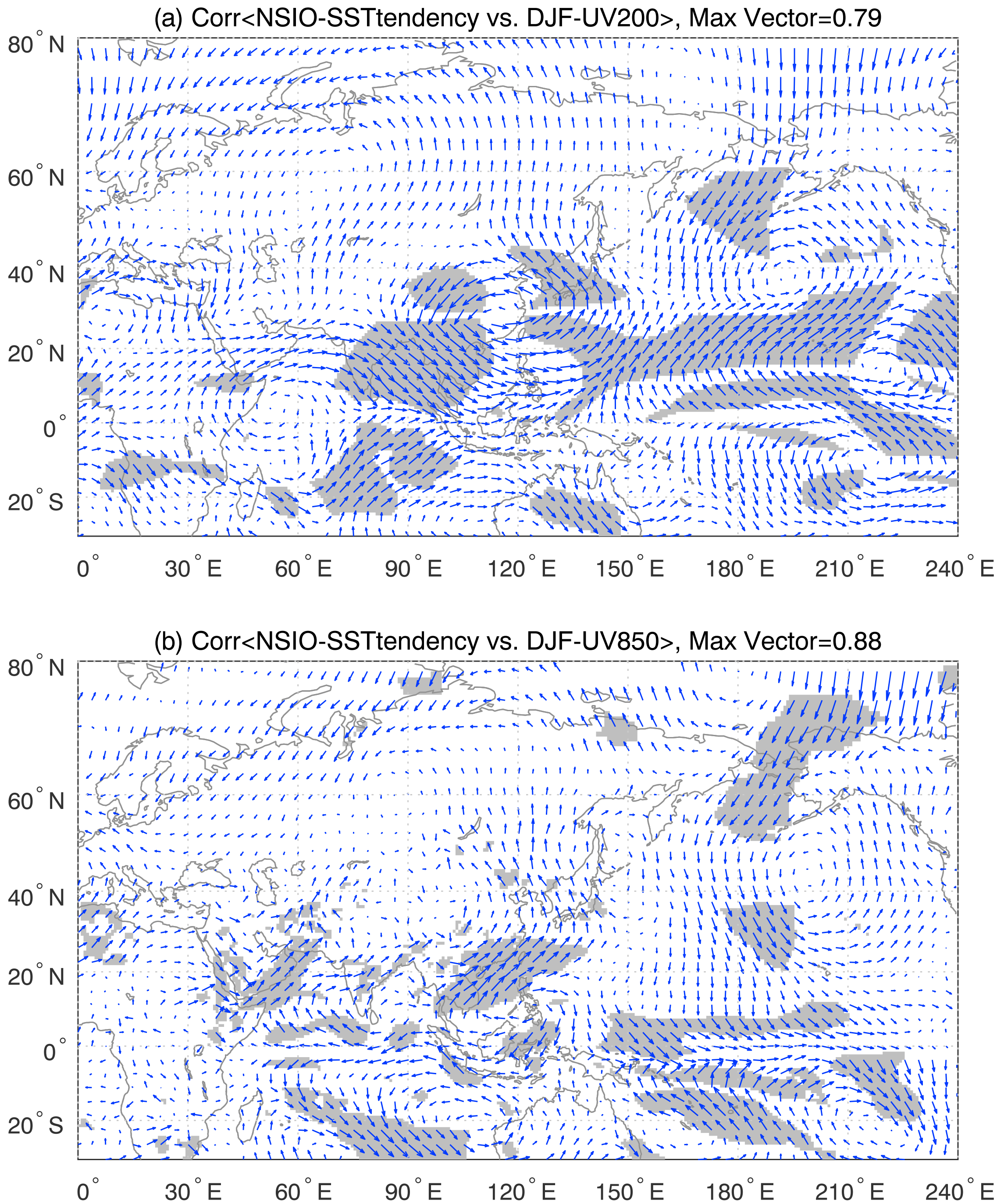

Figure 5. Spatial distribution of high-frequency correlation coefficients between the tendency of SSTa in the NSIO and the winter zonal and meridional winds at (a) 200 hPa and (b) 850 hPa (same as Figure 3). DJF = December-January-February; SSTtendency = sea surface temperature tendency; NSIO = Northwestern Southern Indian Ocean.

weather conditions in NC? The chances of the anomalous signals of the Southern Hemisphere atmosphere persisting for several months and being directly transmitted to the Northern Hemisphere are relatively limited. However, one possible mechanism might be the role of the ocean. Wu et al. (2015) and Liu et al. (2015) highlighted the "memory" effect of sea surface temperature (SST) under abnormal AAO signals. The "ocean-atmosphere coupled bridge" allows the influence of the preceding AAO to persist for an extended period and therefore affect the Northern Hemisphere climate (Li et al., 2013). After a series of correlation analyses, we emphasized the likely roles of the southern Indian Ocean (SIO) in the link

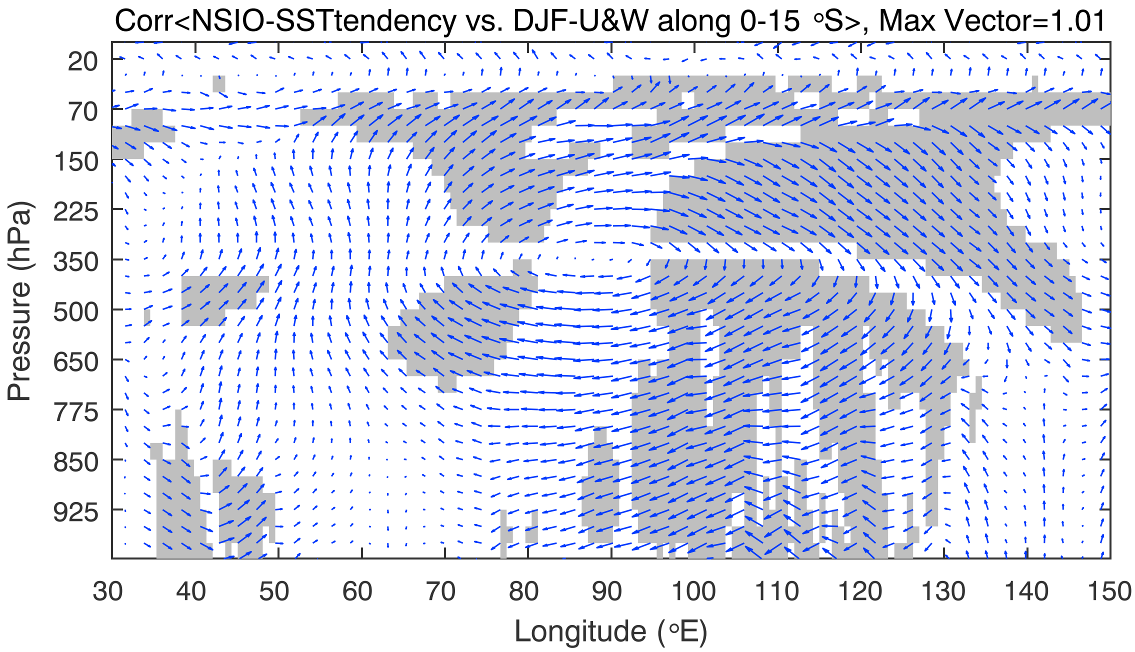

Figure 6. Profiles of high-frequency correlation coefficients between the tendency of SSTa in the NSIO (NSIO-SSTtendency) and mean zonal and vertical winds from the equator to 15°S in boreal winter (the vertical wind velocities were multiplied by 1,000 in Figure 6; if either the zonal or vertical component is significant at the 90% level, then the vectors are shaded in gray). SSTtendency = sea surface temperature tendency; DJF = December-January-February; NSIO = Northwestern Southern Indian Ocean.

between the ASO-AAO and subsequent haze pollution in NC. Here we adopt the SST tendency (SSTtendency) as an indicator for the warming or cooling trends of SST anomalies (SSTa) from the seasons of ASO to DJF, namely, SSTa in DJF minus SSTa in ASO. Then, the high-frequency correlation coefficients between the ASO-AAO and the SSTtendency in the Indian Ocean were examined. The results show that a large area of positive correlations dominated in the Northwestern Southern Indian Ocean (NSIO; area between 5°S to 20°S and 50°E to 80°E, which is shown in the green box in Figures 4a and 4b). These positive correlations indicate that the SSTa in the NSIO from ASO to DJF tends toward warming as the ASO-AAO strengthens. This warming may be associated with anomalous westerlies at the sea surface (vectors in Figure 4a). Compared with the climatological surface wind fields (vectors in Figure 4b), the southeasterly winds from the middle-high latitude to the NSIO tend to weaken during the positive phase of the ASO-AAO. On one hand, the wind speed reduction results in reduced evaporation from the sea surface, which means less latent heat loss and rising SSTs. On the other hand, the anomalous westerlies can lead to a convergence of the Ekman transport, which also causes a rise in SSTs. Thus, it is reasonable that a positive ASO-AAO can cause warming in the NSIO that persists through the boreal winter.

Two possible pathways have been identified by which warming in the NSIO can affect the boreal winter atmospheric circulations in NC. First, warming in the NSIO could lead to diabatic heating and more convective precipitation (Figure 4b), which may provoke a Rossby wave-like response in the upper troposphere, such as an anomalous anticyclone at 200 hPa in the Arabian Sea and its surrounding areas (Figure 5a). The disturbance of the anomalous anticyclone likely causes a series of anomalous wave trains in downstream regions, approximately along the Middle East jet stream to the East Asian jet stream. Thus, an anomalous cyclone and an anomalous anticyclone prevail in the upper troposphere from south Asia to EC and from northeast Asia to the northwestern Pacific, respectively (Figure 5a). This pattern is similar to that demonstrated in the previous studies (Liu et al., 2014; Wang & Chen, 2014; Zheng et al., 2013); namely, the tropical and SIO SST can efficiently cause anomalous Rossby wave activity and then influence the climate over East Asia or even larger areas. These anomalous upper circulations might further influence the regional circulation conditions in the lower troposphere to a certain extent. At 850 hPa, the anomalous southwesterly flow and southern flow dominated over large areas, from the Indo-China Peninsula to the

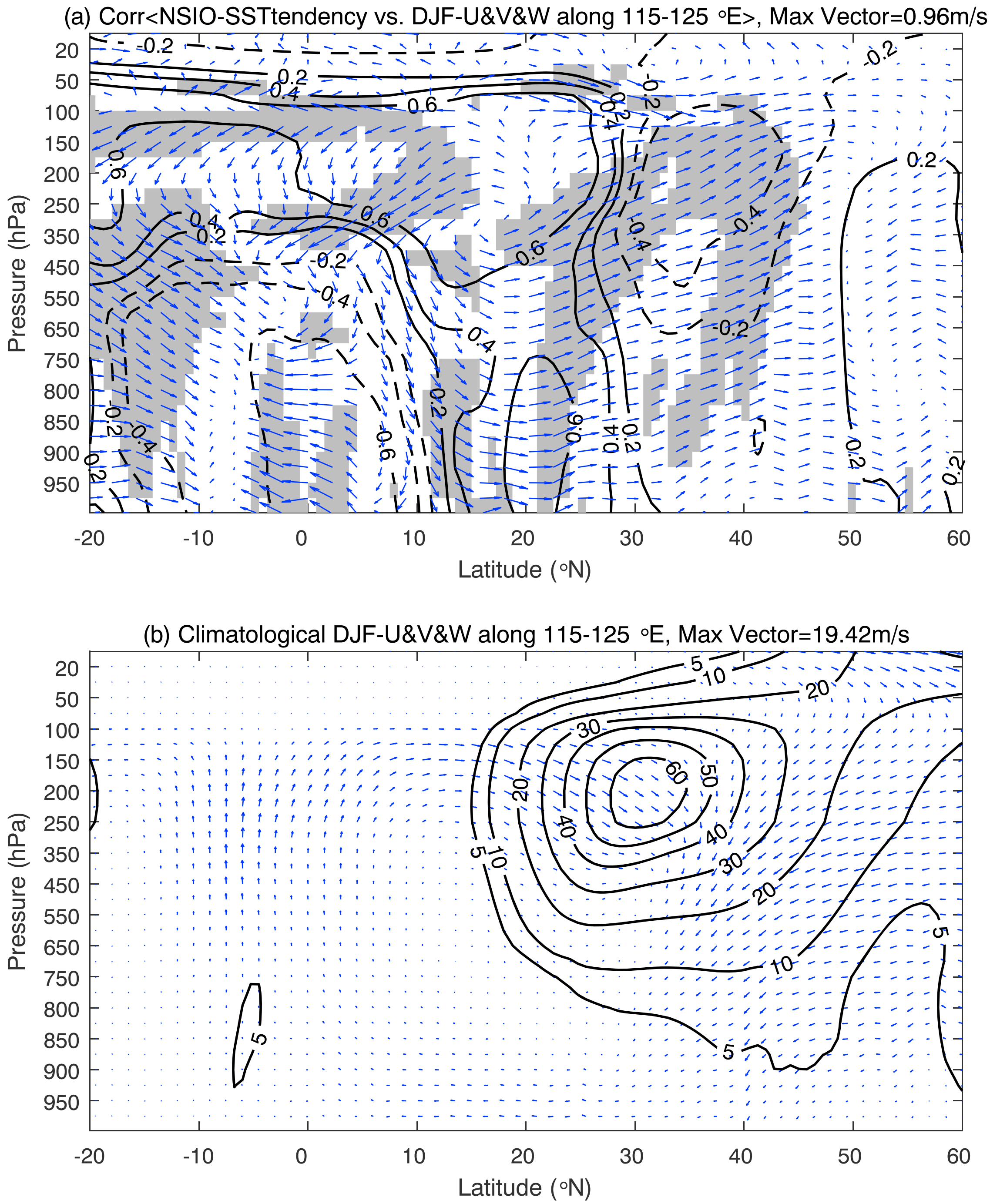

Figure 7. Profiles of high-frequency correlation coefficients between the (a) tendency of SSTa in the NSIO (NSIO-SSTtendency) and meridional and vertical winds (vectors) and zonal winds (contours) and the (b) climatological DJF meridional and vertical winds and zonal winds along 115–125°N (the vertical wind velocities were multiplied by 1,000 in Figure 7b; if either the meridional or vertical component is significant at the 90% level, then the vectors are shaded in gray). SSTtendency = sea surface temperature tendency; DJF = December-January-February; NSIO = Northwestern Southern Indian Ocean.

SC Sea and from the EC Sea to northeastern Asia, respectively (Figure 5b). The drivers of these responses are potentially connected to the warming in the NSIO, which would be derived from the positive ASO-AAO.

The other pathway is that warming in the NSIO causes an anomalous cell of zonal circulation that rises in the warming areas in the SIO and sinks over the Maritime continents (Figure 6). From a meridional perspective, a regional Hadley circulation exists from the Maritime continents to East Asia, which rises over

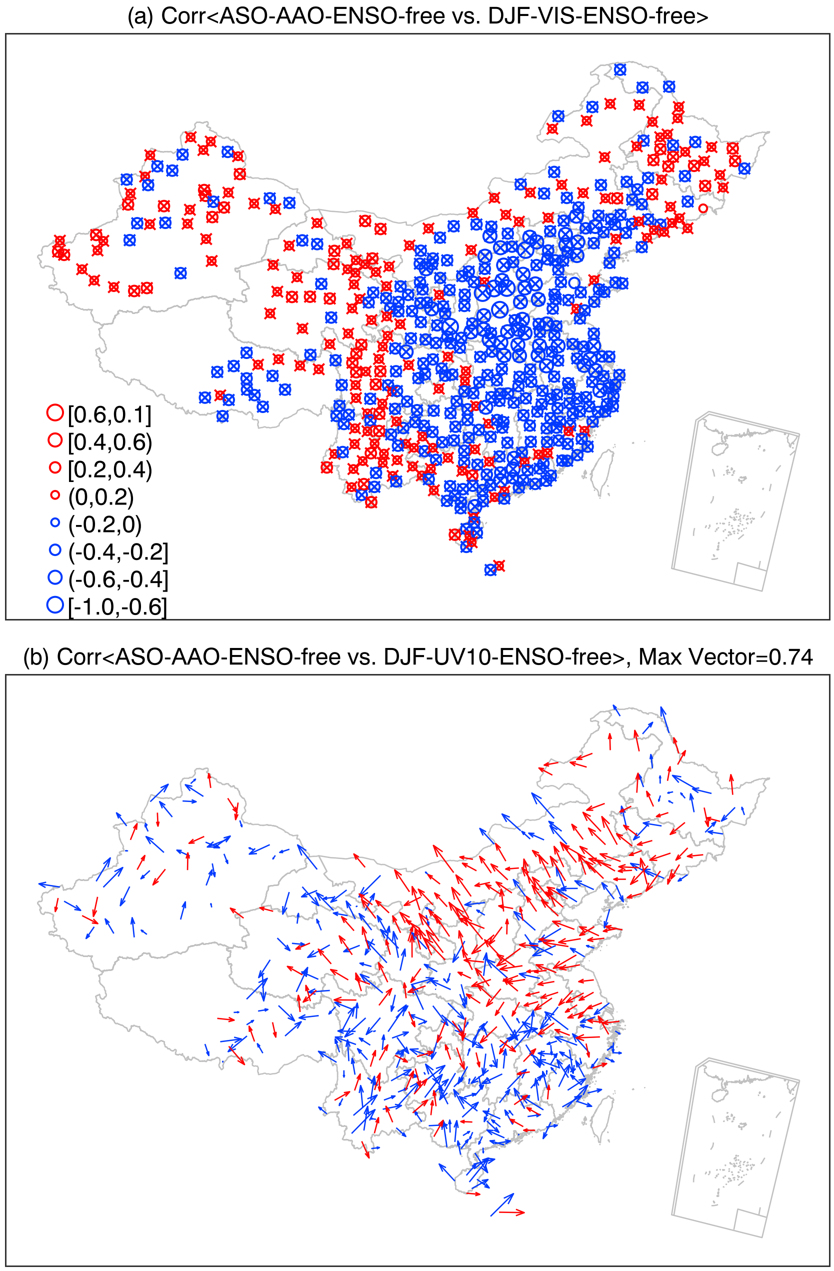

Figure 8. Spatial distribution of the high-frequency (<10 yr) correlation coefficients between the (a) ENSO-removed ASO-AAO (ASO-AAO-ENSO-free) and the ENSO-removed visibility (DJF-VIS-ENSO-free) and (b) the ENSO-removed surface winds (DJF-UV10-ENSO-free) during boreal winters. AAO = Antarctic oscillation; ASO = August-September-October; DJF-VIS = December-January-February visibility; ENSO = El Niño/Southern Oscillation.

the Maritime continents and sinks over northern China (Figure 7b). The sinking motion of the anomalous zonal cell suppresses the upward motion of the regional Hadley circulation in the Maritime continents. Thus, the NSIO warming eventually weakens the Hadley circulation. The weakening Hadley circulation exhibits anomalous sinking motions over the Maritime continents and anomalous southerlies in NC (Figure 7a). The anomalous southerly flow indicates weakening northerlies and more water vapor in NC, namely, the characteristics of a weak East Asian winter monsoon, which are conducive to the formation of haze pollution in NC (Yin & Wang, 2016; Zhang et al., 2016), and vice versa. Thus, to a certain extent, the preceding AAO signal can be a potential predictor for winter haze pollution forecasts or assessments in NC areas.

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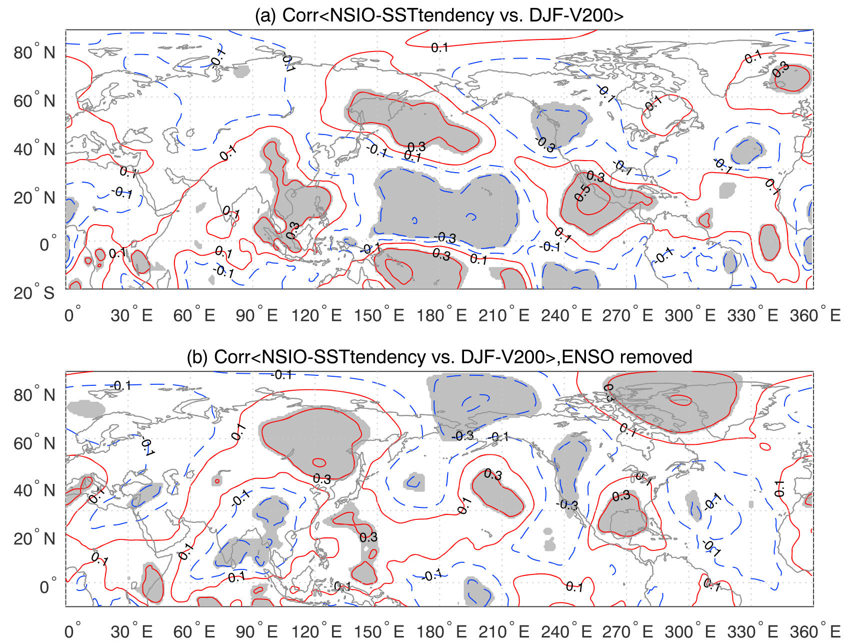

Figure 9. Spatial distribution of high-frequency correlation coefficients between the tendency of SSTa in the NSIO (NSIO-SSTtendency) and the mean zonal wind at 200 hPa (V200) in boreal winter (a) with ENSO and (b) ENSO removed. ENSO = El Niño/Southern Oscillation; NSIO = Northwestern Southern Indian Ocean; DJF = December-January-February. SSTtendency = sea surface temperature tendency; SSTa = sea surface temperature anomalies.

4. Discussions

The correlation analyses after high-pass filtering can effectively eliminate the influence of global warming and other interdecadal changes or long-term trends on the links between haze pollution in NC and AAO activity. However, the interannual climates in both the Southern and Northern Hemispheres are largely impacted by the El Niño/Southern Oscillation (ENSO), especially in low latitudes (Wang et al., 2000). Thus, the data may still show spurious relationships between ASO-AAO and haze pollution in boreal winter in NC due to the simultaneous modulation by ENSO. To examine whether the correspondences between ASO-AAO and haze pollution in China are stable and independent of the ENSO, we removed ENSO signals in the variables of interest through regression analysis. We fit the ASO Niño3.4 SST to the ASO-AAO and DJF-VIS variables using the least squares technique. Then, the estimated ENSO-related components were subtracted from the original time series, and the residuals were regarded as ENSO-free parts (i.e., ASO-AAO-ENSO-free and DJF-VIS-ENSO-free) and subjected to the analysis.

First, we examined the spatial distribution of high-frequency correlation coefficients between the ASO-AAO-ENSO-free and DJF-VIS-ENSO-free values in China. Intuitively, there are very few differences between Figure 1a (correlations between ASO-AAO and DJF-VIS with ENSO) and Figure 8a (correlations between ASO-AAO and DJF-VIS without ENSO). The spatial correlation coefficient between these measurements is 0.996 and significant at the 99% level. After ENSO removal, the high-frequency (original) correlation coefficients between the average visibility in boreal winter in EC, NC, and SC and the ASO-AAO are −0.53 (−0.57), −0.56 (−0.60), and −0.27 (−0.26), respectively. All these values are significant at the 99% level. Unexpectedly, there is a certain improvement in the correlations between the series of ASO-AAO-ENSO-free and DJF-VIS-ENSO-free in NC and EC. Moreover, the ENSO-removed surface winds (Figure 8b), UV850, UV200, and profiles (figures omitted) in boreal winter corresponding to ASO-AAO-ENSO-free are generally the same as the original relationships. These phenomena indicate that the relationships between the ASO-AAO and winter haze pollution in NC may be relatively reliable despite their modulation by the ENSO.

Moreover, we examined the possible difference between the responses of zonal wind at 200 hPa upon the NSIO-SSTtendency when the ENSO is involved or not. Figure 9a presents the spatial distribution of high-frequency correlation coefficients between the NSIO-SSTtendency and V200 without removing the possible influence of the ENSO. Figure 9b shows the correlations between the NSIO-SSTtendency-ENSO-free and V200-ENSO-free, in which the ENSO signals were removed for both the NSIO-SSTtendency and V200 before the correlation analysis. When the ENSO signals were removed, the wave train pattern was even more obvious. Thus, uncertainties may be associated with the preliminary mechanism in the study of the links between ASO-AAO and haze pollution, especially because of possible modulation from the ENSO system. Therefore, additional research is needed to further understand this issue.

5. Conclusions

Based on the daily visibility, relative humidity, and surface wind records from the 542 synoptic meteorological stations around China, the ERA-Interim reanalysis data and the ERSSTv5 SST data, the possible influence of AAO on the boreal winter air pollution in NC since the 1980s was examined in this study. The results showed that the winter visibility in most of eastern China and especially in NC was correlated with the preceding AAO (August-September-October, ASO-AAO). The original (unfiltered) and high-frequency (<10 yr) correlation coefficients between the mean winter visibility (DJF-VIS) in NC and the ASO-AAO are −0.50 and −0.52, respectively, both of which are significant at the 99% level. The significantly negative correlations may suggest that the positive (negative) phase of the ASO-AAO can cause an increase (decrease) of the air pollution in NC in boreal winter on an interannual timescale.

The response of local and regional atmospheric circulations in boreal winter to the ASO-AAO can explicate the significant correlations between DJF-VIS and the ASO-AAO. This study proposes a preliminary mechanism for understanding the influence of the preceding AAO on boreal winter haze pollution in NC. It emphasizes the important roles of SST warming or cooling tendencies in the NSIO and provides two possible pathways by which the NSIO warming may influence the atmosphere in NC. Due to wind speed reductions and the convergence of the Ekman transport, areas in the NSIO tend to warm, which persists through the boreal winter during the positive phase of the ASO-AAO. The warming in the NSIO influences the haze pollution in NC through two possible pathways. One pathway is that warming in the NSIO may cause a Rossby wave-like response in the upper troposphere and then lead to a series of anomalous wave trains along the jet stream. These anomalous upper circulations could further influence the regional circulations related to the haze pollution in NC. The other possible pathway is that warming in the NSIO may cause an anomalous zonal cell that weakens the regional Hadley Circulation from the maritime continents to East Asia. Thus, anomalous southerlies dominate in NC and are directly conducive to the formation of haze pollution, and vice versa. Therefore, the preceding AAO signal likely represents a potential predictor for winter haze pollution forecasts or assessments in NC areas to some extent.

To eliminate the spurious signals that may exist in the results of the study due to the common role of ENSO, all the relationships between DJF-VIS, the ASO-AAO, and others were re-examined after using the least squares technique to remove ENSO influences for all variables. The results show that after ENSO removal, the correlations between the ASO-AAO and DJF-VIS did not decrease; instead, they increased slightly in NC. The original (unfiltered) and high-frequency correlation coefficients between the DJF-VIS in NC and the ASO-AAO were −0.56 and −0.60, respectively. After ENSO removal, the responses of local and regional atmospheric circulations to the ASO-AAO are roughly consistent with the original relationships. Generally, the results suggest that the possible influence of the preceding activity of the AAO on winter air pollution in NC is relatively stable. However, additional research is needed to further understand the complicated mechanism underlying the relationship between the ASO-AAO and haze pollution in NC or even EC since the links may be modulated by the ENSO and other phenomena to a great degree.

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References

Abram, N. J., Robert, M., Francoise, V., Steven, J. P., John, T., & Matthew, H. E. (2014). Evolution of the southern annular mode during the past millennium. *Nature Climate Change*, *4*(7), 564–569. https://doi.org/10.1038/nclimate2235

Baddock, M. C., Strong, C. L., Leys, J. F., Heidenreich, S. K., Tews, E. K., & McTainsh, G. H. (2014). A visibility and total suspended dust relationship. *Atmospheric Environment*, *89*, 329–336. https://doi.org/10.1016/j.atmosenv.2014.02.038

Baumer, D., Vogel, B., Versick, S., Rinke, R., Mohler, O., & Schnaiter, M. (2008). Relationship of visibility, aerosol optical thickness and aerosol size distribution in an ageing air mass over South-West Germany. *Atmospheric Environment*, *42*(5), 989–998. https://doi.org/10.1016/j.atmosenv.2007.10.017

Cao, Z. Q., Sheng, L. F., Liu, Q., Yao, X. H., & Wang, W. C. (2015). Interannual increase of regional haze-fog in North China plain in summer by intensified easterly winds and orographic forcing. *Atmospheric Environment*, *122*, 154–162. https://doi.org/10.1016/j.atmosenv.2015.09.042

Chang, D., Song, Y., & Liu, B. (2009). Visibility trends in six megacities in China 1973–2007. *Atmospheric Research*, *94*(2), 161–167. https://doi.org/10.1016/j.atmosres.2009.05.006

Chen, H. P., & Wang, H. J. (2015). Haze days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. *Journal of Geophysical Research: Atmospheres*, *120*, 5895–5909. https://doi.org/10.1002/2015JD023225

Cheng, X. G., Zhao, T. L., Gong, S. L., Xu, X. D., Han, Y. X., Yin, Y., et al. (2016). Implications of East Asian summer and winter monsoons for interannual aerosol variations over central-eastern China. *Atmospheric Environment*, *129*, 218–228. https://doi.org/10.1016/j.atmosenv.2016.01.037

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Deng, J. J., Xing, Z. Y., Zhuang, B. L., & Du, K. (2014). Comparative study on long-term visibility trend and its affecting factors on both sides of the Taiwan Strait. *Atmospheric Research*, *143*, 266–278. https://doi.org/10.1016/j.atmosres.2014.02.018

Fan, K., & Wang, H. J. (2004). Antarctic oscillation and the dust weather frequency in North China. *Geophysical Research Letters*, *31*, L10201. https://doi.org/10.1029/2004GL019465

Fogt, R. L., Goergens, C. A., Jones, J. M., Schneider, D. P., Nicolas, J. P., Bromwich, D. H., & Dusselier, H. E. (2017). A twentieth century perspective on summer Antarctic pressure change and variability and contributions from tropical SSTs and ozone depletion. *Geophysical Research Letters*, *44*, 9918–9927. https://doi.org/10.1002/2017GL075079

Gong, D. Y., & Luterbacher, J. (2008). Variability of the low-level cross-equatorial jet of the western Indian Ocean since 1660 as derived from coral proxies. *Geophysical Research Letters*, *35*, L01705. https://doi.org/10.1029/2007GL032409

Gong, D. Y., & Wang, S. W. (1999). Definition of Antarctic oscillation index. *Geophysical Research Letters*, *26*(4), 459–462. https://doi.org/10.1029/1999GL900003

Hien, P. D., Loc, P. D., & Dao, N. V. (2011). Air pollution episodes associated with East Asian winter monsoons. *Science of the Total Environment*, *409*(23), 5063–5068. https://doi.org/10.1016/j.scitotenv.2011.08.049

Huang, B. Y., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature version 5 (ERSSTv5), upgrades, validations, and intercomparisons. *Journal of Climate*, *30*(20), 8179–8205. https://doi.org/10.1175/JCLI-D-16-0836.1

Jeong, J. I., & Park, R. J. (2013). Effects of the meteorological variability on regional air quality in East Asia. *Atmospheric Environment*, *69*, 46–55. https://doi.org/10.1016/j.atmosenv.2012.11.061

Jones, J. M., Gille, S. T., Goosse, H., Abram, N. J., Canziani, P. O., Charman, D. J., et al. (2016). Assessing recent trends in high-latitude southern hemisphere surface climate. *Nature Climate Change*, *6*(10), 917–926. https://doi.org/10.1038/nclimate3103

Jones, T. R., Roberts, W. H. G., Steig, E. J., Cuffey, K. M., Markle, B. P., & White, J. W. C. (2018). Southern Hemisphere climate variability forced by Northern Hemisphere ice-sheet topography. *Nature*, *554*(7692), 351–355. https://doi.org/10.1038/nature24669

Lang, X. M. (2008). Prediction model for spring dust weather frequency in North China. *Science China Earth Sciences*, *51*(5), 709–720.

Li, J. P., Ren, R. C., Qi, Y. Q., Wang, F. M., Lu, R. Y., Zhang, R. Q., et al. (2013). Progress in air-land-sea interactions in Asia and their role in global and Asian climate change (in Chinese). *Chinese Journal of Atmospheric Sciences*, *37*, 518–538.

Li, Q., Zhang, R. H., & Wang, Y. (2016). Interannual variation of the wintertime fog–haze days across central and eastern China and its relation with East Asian winter monsoon. *International Journal of Climatology*, *36*(1), 346–354. https://doi.org/10.1002/joc.4350

Li, Z. Q., Guo, J. P., Ding, A. J., Liao, H., Liu, J. J., Sun, Y. L., et al. (2017). Aerosol and boundary-layer interactions and impact on air quality. *Natural Science Review*, *4*(6), 810–833. https://doi.org/10.1093/nsr/nwx117

Li, Z. Q., Lau, W. K.-M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., et al. (2016). Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics*, *54*, 866–929. https://doi.org/10.1002/2015RG000500

Liu, T., Li, J. P., & Zheng, F. (2015). Influence of the boreal autumn southern annular mode on winter precipitation over land in the Northern Hemisphere. *Journal of Climate*, *28*(22), 8825–8839. https://doi.org/10.1175/JCLI-D-14-00704.1

Liu, Y. Y., Wang, L., Zhou, W., & Chen, W. (2014). Three Eurasian teleconnection patterns: Spatial structures, temporal variability, and associated winter climate anomalies. *Climate Dynamics*, *42*(11-12), 2817–2839. https://doi.org/10.1007/s00382-014-2163-z

Lovenduski, N. S., & Gruber, N. (2005). Impact of the southern annular mode on Southern Ocean circulation and biology. *Geophysical Research Letters*, *32*, L11603. https://doi.org/10.1029/2005GL022727

Lu, C. H., & Guan, Z. Y. (2009). On the interannual variation in spring atmospheric inter-hemispheric oscillation linked to synchronous climate in China. *Progress in Natural Science*, *19*(9), 1125–1131. https://doi.org/10.1016/j.pnsc.2009.01.006

Mao, R., Gong, D. Y., Yang, J., Zhang, Z. Y., Kim, S. J., & He, H. Z. (2013). Is there a linkage between the tropical cyclone activity in the southern Indian Ocean and the Antarctic oscillation? *Journal of Geophysical Research: Atmospheres*, *118*, 8519–8535. https://doi.org/10.1002/jgrd.50666

Marais, E. A., Jacob, D. J., Jimenez, J. L., Campuzano-Jost, P., Day, D. A., Hu, W., et al. (2016). Aqueous-phase mechanism for secondary organic aerosol formation from isoprene: Application to the Southeast United States and co-benefit of SO_2 emission controls. *Atmospheric Chemistry and Physics*, *16*(3), 1603–1618. https://doi.org/10.5194/acp-16-1603-2016

Mues, A., Manders, A., Schaap, M., Kerschbaumer, A., Stern, R., & Builtjes, P. (2012). Impact of the extreme meteorological conditions during the summer 2003 in Europe on particulate matter concentrations. *Atmospheric Environment*, *55*, 377–391. https://doi.org/10.1016/j.atmosenv.2012.03.002

Nan, S. N., & Li, J. P. (2003). The relationship between the summer precipitation in the Yangtze River valley and the boreal spring southern hemisphere annular mode. *Geophysical Research Letters*, *30*(24), 2266. https://doi.org/10.1029/2003GL018381

Ramsey, N. R., Petra, M. K., & Berrien, M. (2014). The impact of meteorological parameters on urban air quality. *Atmospheric Environment*, *86*, 58–67. https://doi.org/10.1016/j.atmosenv.2013.12.006

Reason, C. J. C., & Rouault, M. (2005). Links between the Antarctic oscillation and winter rainfall over western South Africa. *Geophysical Research Letters*, *32*, L07705. https://doi.org/10.1029/2005GL022419

Sabetghadam, S., Farhang, A. G., & Golestani, Y. (2012). Visibility trends in Tehran during 1958-2008. *Atmospheric Environment*, *62*, 512–520. https://doi.org/10.1016/j.atmosenv.2012.09.008

Sun, Y. L., Li, J. P., & Sun, C. (2016). Rapid formation and evolution of an extreme haze episode in northern China during winter 2015. *Scientific Reports*, *6*(1), 27151. https://doi.org/10.1038/srep27151

Tao, M. H., Chen, L. F., Xiong, Z. X., Zhang, M. G., Ma, P. F., Tao, J. H., & Wang, Z. F. (2014). Formation process of the widespread extreme haze pollution over northern China in January 2013: Implications for regional air quality and climate. *Atmospheric Environment*, *98*, 417–425. https://doi.org/10.1016/j.atmosenv.2014.09.026

Thompson, D. W. J., & Wallace, J. M. (2000). Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate*, *13*(5), 1000–1016. https://doi.org/10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2

Tie, X., Zhang, Q., He, H., Gao, J. J., Han, S. Q., Gao, Y., et al. (2015). A budget analysis of the formation of haze in Beijing. *Atmospheric Environment*, *100*, 25–36. https://doi.org/10.1016/j.atmosenv.2014.10.038

Wang, B., Wu, R., & Fu, X. (2000). Pacifice East Asia teleconnection: How does ENSO affect east Asian climate? *Journal of Climate*, *13*(9), 1517–1536. https://doi.org/10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2

Wang, H. J., & Chen, H. P. (2016). Understanding the recent trend of haze pollution in eastern China: Roles of climate change. *Atmospheric Chemistry and Physics*, *16*(6), 4205–4211. https://doi.org/10.5194/acp-16-4205-2016

Wang, H. J., & Fan, K. (2005). Central-North China precipitation as reconstructed from the Qing dynasty: Signal of the Antarctic atmospheric oscillation. *Geophysical Research Letters*, *32*, L24705. https://doi.org/10.1029/2005GL024562

Wang, L., & Chen, W. (2014). An intensity index for the East Asian winter monsoon. *Journal of Climate*, *27*(6), 2361–2374. https://doi.org/10.1175/JCLI-D-13-00086.1

Wang, T., Nie, W., Gao, J., Xue, L. K., Gao, X. M., Wang, X. F., et al. (2010). Air quality during the 2008 Beijing Olympics: Secondary pollutants and regional impact. *Atmospheric Chemistry and Physics*, *10*(16), 7603–7615. https://doi.org/10.5194/acp-10-7603-2010

Wen, C. C., & Yeh, H. H. (2010). Comparative influences of airborne pollutants and meteorological parameters on atmospheric visibility and turbidity. *Atmospheric Research*, *96*(4), 496–509. https://doi.org/10.1016/j.atmosres.2009.12.005

Whiteaker, J. R., Suess, D. T., & Prather, K. A. (2002). Effects of meteorological conditions on aerosol composition and mixing state in Bakersfield, CA. *Environmental Science & Technology*, *36*(11), 2345–2353. https://doi.org/10.1021/es011381z

Wu, G. X., Li, Z. Q., F, C. B., Zhang, X. Y., Zhang, R. Y., Zhang, R. H., et al. (2016). Advances in studying interactions between aerosols and monsoon in China. *Science China Earth Sciences*, *59*(1), 1–16. https://doi.org/10.1007/s11430-015-5198-z

Wu, Q. Z., Wang, Z. F., Gbaguidi, A., Gao, C., Li, L. N., & Wang, W. (2011). A numerical study of contributions to air pollution in Beijing during CAREBeijing-2006. *Atmospheric Chemistry and Physics*, *11*(12), 5997–6011. https://doi.org/10.5194/acp-11-5997-2011

Wu, Z. W., Dou, J., & Lin, H. (2015). Potential influence of the November-December Southern Hemisphere annular mode on the East Asian winter precipitation: A new mechanism. *Climate Dynamics*, *44*(5-6), 1215–1226. https://doi.org/10.1007/s00382-014-2241-2

Wu, Z. W., Li, J. P., Wang, B., & Liu, X. H. (2009). Can the southern hemisphere annular mode affect China winter monsoon? *Journal of Geophysical Research*, *114*, D11107. https://doi.org/10.1029/2008JD011501

Xu, X. D., Wang, Y. J., Zhao, T. L., Cheng, X. H., Meng, Y. Y., & Ding, G. A. (2015). "Harbor" effect of large topography on haze distribution in eastern China and its climate modulation on decadal variations in haze China (in Chinese). *Chinese Science Bulletin*, *60*(12), 1132–1143. https://doi.org/10.1360/N972014-00101

Yin, Z. C., & Wang, H. J. (2016). Seasonal prediction of winter haze days in the north-central North China plain. *Atmospheric Chemistry and Physics*, *60*(15), 1395–1400.

Yin, Z. C., & Wang, H. J. (2017). Role of atmospheric circulations on haze pollution in December 2016. *Atmospheric Chemistry and Physics*, *17*(18), 11,673–11,681. https://doi.org/10.5194/acp-17-11673-2017

Yin, Z. C., Wang, H. J., & Chen, H. P. (2017). Understanding severe winter haze events in the North China plain in 2014: Roles of climate anomalies. *Atmospheric Chemistry and Physics*, *17*(3), 1641–1651. https://doi.org/10.5194/acp-17-1641-2017

Zhang, R. H., Li, Q., & Zhang, R. N. (2014). Meteorological conditions for the persistent severe fog and haze event over eastern China in January 2013. *Science China Earth Sciences*, *57*, 26–35.

Zhang, Z. Y., Gong, D. Y., Mao, R., Kim, S. J., Xu, J., Zhao, X. J., & Ma, Z. Q. (2017). Cause and predictability for the severe haze pollutions in downtown Beijing during November–December 2015. *Science of the Total Environment*, *592*, 627–638. https://doi.org/10.1016/j.scitotenv.2017.03.009

Zhang, Z. Y., Xu, X. D., Qiao, L., Gong, D. Y., Kim, S. J., Wang, Y. J., & Mao, R. (2018). Numerical simulations of the effects of regional topography on haze pollution in Beijing. *Scientific Reports*, *8*. https://doi.org/10.1038/s41598-018-23880-8 2018

Zhang, Z. Y., Zhang, X. L., Gong, D. Y., Kim, S. J., Mao, R., & Zhao, X. J. (2016). Possible influence of atmospheric circulations on winter hazy pollution in Beijing-Tianjin-Hebei region, northern China. *Atmospheric Chemistry and Physics*, *16*(2), 561–571. https://doi.org/10.5194/acp-16-561-2016

Zhang, Z. Y., Zhang, X. L., Gong, D. Y., Quan, W. J., Zhao, X. J., Ma, Z. Q., & Kim, S. J. (2015). Evolution of surface O_3 and $PM_{2.5}$ concentrations and their relationships with meteorological conditions over the last decade in Beijing. *Atmospheric Environment*, *108*, 67–75. https://doi.org/10.1016/j.atmosenv.2015.02.071

Zheng, G. J., Duan, F. K., & Su, H. (2015). Exploring the severe winter haze in Beijing: The impact of synoptic weather, regional transport and heterogeneous reactions. *Atmospheric Chemistry and Physics*, *15*(6), 2969–2983. https://doi.org/10.5194/acp-15-2969-2015

Zheng, J., Liu, Q. Y., Wang, C. Z., & Zheng, X. T. (2013). Impact of heating anomalies associated with rainfall variations over the Indo-Western pacific on Asian atmospheric circulation in winter. *Climate Dynamics*, *40*(7-8), 2023–2033. https://doi.org/10.1007/s00382-012-1478-x