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Key Points:
- Analysis performed on daily visibility data from 1960 to 2012
- Haze primarily occurs in boreal winter and in morning in North China
- Haze occurrence closely linked to northward activity of East Asian jet stream

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Haze Days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012

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Abstract Haze is a severe hazard that greatly influences traffic and daily life with great economic losses and threats to human health. To enhance understanding of the haze occurrences, this study examined the haze variations over North China and their associated atmospheric circulations for the period of 1960–2012 using daily visibility data. Results indicate that the haze events over this region primarily occur in boreal winter of year and mainly in the morning of day. The results of the analysis of the long-term variations indicate that the annual haze days were relatively few in the 1960s but increased steeply in the 1970s and have remained stable to the present. Some differences are obvious among seasons. A stably increasing trend is discernable in summer and autumn, relatively low in the 1960s and the 1990s–2000s and relatively high in the 1970s–1980s in spring and winter. Haze variations in urban regions are quite similar to haze variations in rural regions but with more haze days in urban regions because of the high aerosol emissions. Further analyses indicate that the occurrences of severe haze events in boreal winter generally correlate with the weakened northerly winds and the development of inversion anomalies in the lower troposphere, the weakened East Asian trough in the midtroposphere, and the northward East Asian jet in the high troposphere. All of these factors provide a favorable atmospheric background for the maintenance and development of haze events in this region.

1. Introduction

In January 2013, eastern China was hit by a persistent and heavy haze event that affected more than 800 million people. During those days, Beijing reached its highest level of air pollution, which led to the first haze orange alert in Beijing's meteorological history [e.g., *Ding and Liu*, 2014; *Zhang et al.*, 2014]. Since then, both government bodies and the general public have paid more attention to the issue of haze. For example, in September 2013, an air pollution prevention action plan stipulated strict controls on coal consumption, industry production, vehicles, etc.

In recent years, with the intensification of air pollution in China, more haze days with increased aerosol concentration have been detected during winter and spring [e.g., *Niu et al.*, 2010; *Ding and Liu*, 2014; *Wang et al.*, 2015]. Meanwhile, the visibility reduction is obvious in some Chinese mega cities and even throughout the country [*Qiu and Yang*, 2000; *Xu*, 2001; *Che et al.*, 2007; *Deng et al.*, 2008; *Chang et al.*, 2009; *Wu et al.*, 2012; *Fu et al.*, 2013]. The high aerosol concentrations and low visibility have resulted in severe environmental and climate problems. For example, the increased aerosol particles on the haze days reduce visibility [*Qiu and Yang*, 2000; *Luo et al.*, 2001; *Deng et al.*, 2008; *Li et al.*, 2009; *Guo et al.*, 2011; *Wu et al.*, 2014], thus delaying traffic [*Wu et al.*, 2005]. Additionally, a direct effect can be detected from the aerosols on radiative forcing and infrared radiation in the atmosphere [*Luo et al.*, 2001; *Qian et al.*, 2006; *Li et al.*, 2010; *Niu et al.*, 2010]. In addition to these effects, haze can also cause serious health problems, from respiratory illnesses to heart disease, premature death, and cancer [*Pope and Dockery*, 2006; *Wang and Mauzerall*, 2006; *Xie et al.*, 2014]. In particular, the number of pediatric patients with pneumonia is reported to have increased dramatically in China in recent years [*Xu et al.*, 2013] because of increased aerosol concentrations. Therefore, in-depth investigations of the variations in haze events are clearly necessary for enhanced understanding as well as an improved ability to predict haze events.

Previous studies have documented that the variations in haze days in China varied in different regions, with increases in economically developed eastern China but decreases in the less economically developed northeastern or northwestern regions of this country [e.g., *Niu et al*., 2010; *Wu et al*., 2010; *Ding and Liu*, 2014]. Furthermore, this increasing trend in eastern China has become much more pronounced since 2001 [*Sun et al*., 2013]. Early studies have suggested that this long-term increase in haze is closely related to the human activities. The rapid urbanization and economic development in China cause increased pollutants to be emitted into the atmosphere, which has led to an increase in haze days in recent decades [*Wang et al*., 2013]. In Beijing, vehicles are generally considered the greatest source of particulate matter 2.5 ($PM_{2.5}$) (fine particulate matter), accounting for 25% of the pollution, and coal combustion and cross-regional transport are the second greatest source, both accounting for 19%, despite there still being some debate regarding the contributions of these sources [*He et al*., 2013; *Zhang et al*., 2013]. Secondary inorganic aerosols and coal combustion are also the two main contributors to $PM_{2.5}$ in the other regions in China, such as in Chengdu City (in southwestern China), accounting for $37 \pm 18\%$ and $20 \pm 12\%$ of the pollutants, respectively [*Tao et al*., 2014]. In addition to the effects of human activities, the increased number of haze days in eastern China may be associated with the descending trends in the surface wind speed [*Xu et al*., 2006; *Gao*, 2008; *Niu et al*., 2010] and the relative humidity in the atmosphere [*Ding and Liu*, 2014] because of climate warming. *Wu et al*. [2008] indicated that there are stronger zonal circulations in the midtroposphere and weaker winds on the surface when the heavy haze occurs in the Pearl River Delta region of China. *Wang et al*. [2015] further revealed that the declining Arctic Sea ice can intensify haze pollution in eastern China and account for approximately 45%–67% of the interannual to interdecadal variability of haze days. Thus, the variations of haze days in China are also closely associated with climate change.

North China is one of the most populated and most polluted regions in China. In recent years, rapid economic development has led to heavy atmospheric aerosol loadings in this region, which has caused severe environmental and climate problems [*Giorgi et al*., 2002; *Qian et al*., 2003; *Han et al*., 2009; *Zhang et al*., 2009; *Li et al*., 2011; *Liao et al*., 2015]. The characteristics of the aerosol particles on haze days and the aerosol particles' effects on the formation of haze have been well documented for this region [*Niu et al*., 2010; *Quan et al*., 2011; *Ji et al*., 2012; *Li et al*., 2013]. However, the related atmospheric background fields on haze days in this region have not been clearly understood from climatic perspectives, although the ambient conditions have been explored in some case studies. For example, the severe haze event in January 2013 in eastern China was closely related to the weakened surface winds and the anomalous inversion in the near surface that are favorable to a haze event's maintenance and development [*Zhang et al*., 2014]. A better understanding of the climate conditions of haze events in North China may lead to an improvement in the prediction of haze days and the formation of an early warning system. Given the importance of this goal, the analyses of this study primarily include (1) the characteristics of haze occurrences over the past decades and (2) the associated atmospheric background fields for these events.

2. Data and Method

The data used in this study are mainly from the strictly quality-controlled Chinese observational data set, collected by the National Meteorological Information Center of China and including relative humidity, visibility, and wind speed. These data include observations 4 times per day: 02:00 local time (LT), 08:00 LT, 14:00 LT, and 20:00 LT. Seventy-eight stations in North China were selected for analysis in this study; consecutive records were kept from 1960 to 2012, including 33 urban sites and 45 rural sties (Figure 1). In general, the urban sites mainly located in the large cities that with high population density (the number of resident exceeding 200,000) and rapidly economy development, and the rural sites located in the small cities with low population density (below 200,000) and slowly economy development. This division principle of the cities is according to the "Advice about adjusting the standard of urban size" proposed by the Chinese government in 29 October 2014. Additionally, the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) daily atmospheric reanalysis data from 1 January 1960 to 31 December 2012, with a horizontal resolution of $2.5° \times 2.5°$ in longitude by latitude, are used for the analysis of the climatic conditions on haze days. Identical meteorological factors were also analyzed from the ERA-Interim reanalysis calculated from the data gathered 4 times per day from 1 January 1979 to 31 December 2012, with a horizontal resolution of $1.5° \times 1.5°$. In addition, the monthly reanalysis data from the NCEP/NCAR and ERA-Interim were also employed here.

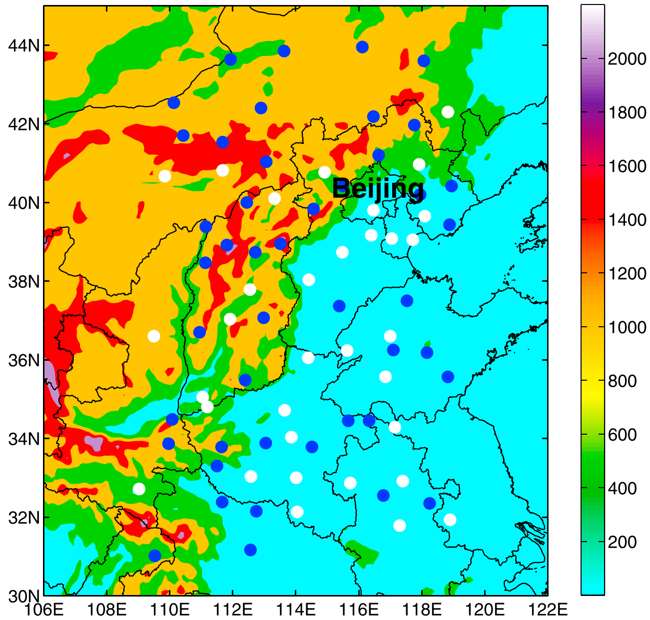

Figure 1. The topographic map (shading; units: m) of North China and the locations of 78 observation sites, including 33 urban sites (white circles) and 45 rural sites (blue circles).

In Chinese site measurements, the visibility data were collected in different forms before and after 1980 because of the different observational rules, with records in the form of a scale before 1980 and in kilometers after 1980 [*Qian and Giorgi*, 2000; *Qian et al*., 2009; *Ding and Liu*, 2014]. Thus, it is necessary to address these data and maintain their consistency before analysis. In this study, we unified all the visibility data from 1960 to 1979 into data in the form of visibility in kilometer [*Qin et al*., 2010]. Table 1 shows the contrasting relations between the visibility scale and the corresponding horizontal distance. According to this relation, the visibility data in kilometers from 1980 to 2012 were first converted to the scale. Then, the optimal distance was calculated as the average of all distances for each scale from 1980 to 2012; the estimated results are shown in Table 1. Finally, the visibility data in scale were replaced by the estimated corresponding distance for each scale from 1960 to 1979 as well as from 1980 to 2012. Theoretically, each visibility scale can be enclosed by any value between corresponding distance intervals, such as the midvalue. However, as the interval of visibility distance corresponded to the scale is not equally spaced, the visibility distance before 1980s would be overestimated if replaced by midvalue, which would cause the data discontinuous around 1980 as well [*Qin et al*., 2010; *Wu et al*., 2012]. Figure 2 shows the contrasting results of the annual variations of the observed and estimated visibility in North China. Clearly, the variations and the descending trend in visibility in North China are accurately reproduced by the estimated results, and their correlation coefficient can be up to 0.98 from 1980 to 2012. Admittedly, visibility is underestimated relative to observation, ranging from −5.4% to −0.7%, and the average error is −2.9%, which will be included in defining haze occurrences. To maintain the data consistency before and after 1980, the estimated visibility from 1960 to 2012 was employed to replace the observed data in 1980–2012 for haze definitions and analyses.

Generally, measured haze occurrences are defined based on the observations of relative humidity and visibility according to specified criteria, which vary between organizations (e.g., World Meteorological Organization and UK Met Office) and personal views [e.g., *Wu*, 2006; *Vautard et al*., 2009; *Ding and Liu*, 2014]. We adopted a widely used comprehensive judgment method with visibility of less than 10 km and relative humidity at less than 90%. Early studies have documented that haze can easily be separated from fog when the value of the relative humidity is set to less than 90% [*Schichtel et al*., 2001; *Doyle and Dorling*, 2002]. The effect of dust is also excluded because of its low visibility. However, the dust data in China are not

Table 1. Visibility Ranges and Corresponding Estimations for Each Visibility Scale

Scale	Visibility Ranges (km)	Estimated Visibility (km)
0	<0.05	0.025
1	0.05–0.2	0.10
2	0.2–0.5	0.30
3	0.5–1.0	0.72
4	1.0–2.0	1.42
5	2.0–4.0	2.66
6	4.0–10.0	7.07
7	10.0–20.0	13.30
8	20.0–50.0	25.74
9	>50.0	50.01

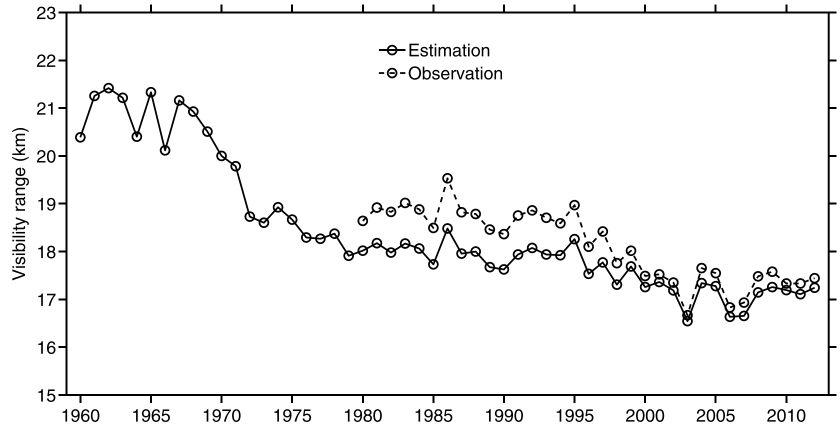

Figure 2. The regional averaged annual variations of the observed and estimated visibility in North China. Units: km.

opened publicly, and a substitute method is generally used to define the dust event in the operational work in China, with the surface wind speed larger than 7 m/s. Thus, the wind speed should be lower than 7 m/s when the haze occurred. If visibility, relative humidity, and wind speed meet the above criterions once among the 4 times per day, haze is considered to have occurred that day. The number of monthly haze occurrences is calculated as the sum of the daily series, and the regional averages are computed as the simple means of the sites.

3. Haze Variations in North China

Figure 3a shows the annual cycle of the haze occurrences in North China calculated from data gathered over the past five decades. The average climate value of the number of annual haze days was 80.6 d/yr, and the numbers of haze days were reported to increase for months (figure not shown). Figure 3a indicates that the number of haze days varies widely in different months and measured sites. However, the regional averaged results indicate that the haze events in North China occur mainly in boreal winter, accounting for approximately 32.8% of the annual haze occurrences. In addition to the effects of the local atmospheric

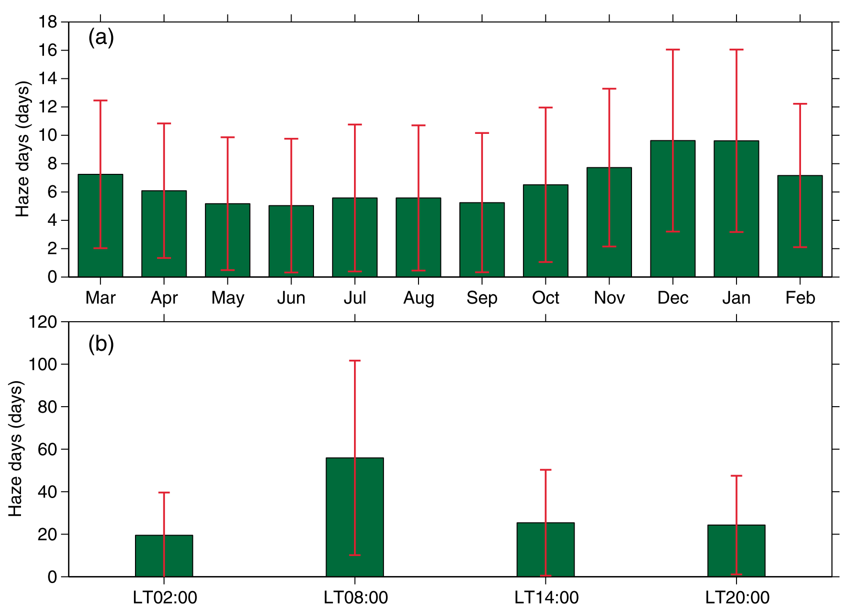

Figure 3. Plots of (a) annual and (b) diurnal cycles of haze days in North China for the period 1960–2012. The error bar represents one standard deviation among the measured sites. Units: days.

conditions, the high occurrence of haze events during boreal winter primarily results from increased coal combustion used for heat and weaker wet scavenging due to less precipitation. The numbers in spring and autumn are relatively smaller, accounting for 23.0% and 24.2%, respectively, of the annual occurrences. Particularly in boreal March and November, these two months that still requiring heating, the haze occurrences are up significantly to 9.0% and 9.6%, respectively. Relatively fewer haze days are reported in boreal summer in this region, mainly because of more rainy days in this time, with only 16.0 d/yr, accounting for approximately 19.9% of the annual haze days.

Using the observed data collected 4 times per day, the average climate diurnal cycle of haze events was explored for the region of North China (Figure 3b). Clearly, the haze events primarily occurred at 08:00 LT, accounting for approximately 44.7% of all occurrences. It is easy to understand the reason for the high concentration at this time. First, 08:00 LT is rush hour. Second, the strong inversion in the near-surface generally occurs in conjunction with low atmospheric pressure at this time, limiting the aerosol transports in vertical and horizontal directions. The occurrences at 14:00 LT and 20:00 LT are relatively fewer than at 08:00 LT, accounting for 20.3% and 19.4%, respectively. At 02:00 LT, just 15.6% of haze events are reported in this region.

Figure 4 presents the long-term variations in haze occurrences and visibility averages over North China from 1960 to 2012 in annual and seasonal scales. The 78 measurement sites over North China are also classified into 33 urban sites and 45 rural sites (Figure 1); their corresponding evolution is shown in Figure 4. The majority of these urban measurement sites (Beijing, Tianjin, Baoding, etc.) are located in relatively large cities with relatively higher aerosol emissions, and the rural sites are primarily located in the small cities, with relatively lower aerosol emissions, which generally results in more hazy days in urban sites than in rural sites.

The annual occurrences of haze increased over North China from 1960 to 2012, and a steep increase occurred in the 1970s. The regional average number of haze days in the 1960s was approximately 51.5 d/yr, which subsequently increased significantly but has remained stable since the late 1970s. In the 2000s, the number of haze days increased to 89.7 d/yr, an increase of 74% compared to the 1960s (Table 2). Correspondingly, visibility reportedly decreases significantly because of the increased concentrations of aerosol particles in the atmosphere. The correlation coefficient between the number of haze days and the visibility reached -0.91 during the past five decades and even higher (-0.92) after both the trends deleted. Similar change characteristics can be observed from the evolution of these trends in the urban and rural sites, with more haze days in urban sites and fewer in rural sites. Meanwhile, visibility in both urban and rural regions decreased from 1960 to 2012, although the decrease was relatively higher in urban sites than in rural sites. According to the statistics, haze days in the urban sites increased from 83.6 d/yr in the 1960s to 132.5 d/yr in the 2000s, an increase of 58%. For the rural sites, the increase in haze days was generally smaller than in the urban sites, increasing from 27.8 d/yr in the 1960s to 58.4 d/yr in the 2000s. However, the value of the relative change in haze days is relatively higher in rural sites than in urban sites, and the number of haze days in rural sites is reported to increase by 110% in the 2000s when compared to 1960s.

The long-term variations in haze days over North China differ by seasons as well as over both urban and rural sites. In boreal spring and winter, the number of haze days shows an obvious interdecadal change, relatively smaller in the 1960s and from the 1990s to the 2000s and relatively higher in the 1970s and 1980s. The steep increase in the 1970s corresponds to the transition period from good visibility to poor visibility in this region. However, the visibility has remained stable since the early 1980s, despite being dominated by strong interannual variability. The reason for the decrease in haze days since the 1990s is not clear, and more research are necessary. Early studies indicate that the number of haze days in boreal winter has significantly increased in recent years over eastern China [*Wang et al.*, 2015], quite different from the long-term variation over North China. These findings suggest that the significant increase in haze days in recent years has primarily occurred over southern China, which is consistent with a previous study [*Ding and Liu*, 2014]. Although the number of haze days in the 1960s and from the 1990s to the 2000s is smaller than in the 1970s and 1980s, the haze events remain frequent occurrences in recent years, similar to the numbers recorded in the 1960s. In the spring, haze days are reported to have increased from 20.9 d/yr in the 1960s to 26.1 d/yr in the 2000s in urban sites and from 8.1 d/yr to 11.4 d/yr in rural sites. In the winter, haze days increase from 32.5 d/yr to 36.9 d/yr in urban sites and from 10.6 d/yr to 17.6 d/yr in rural sites.

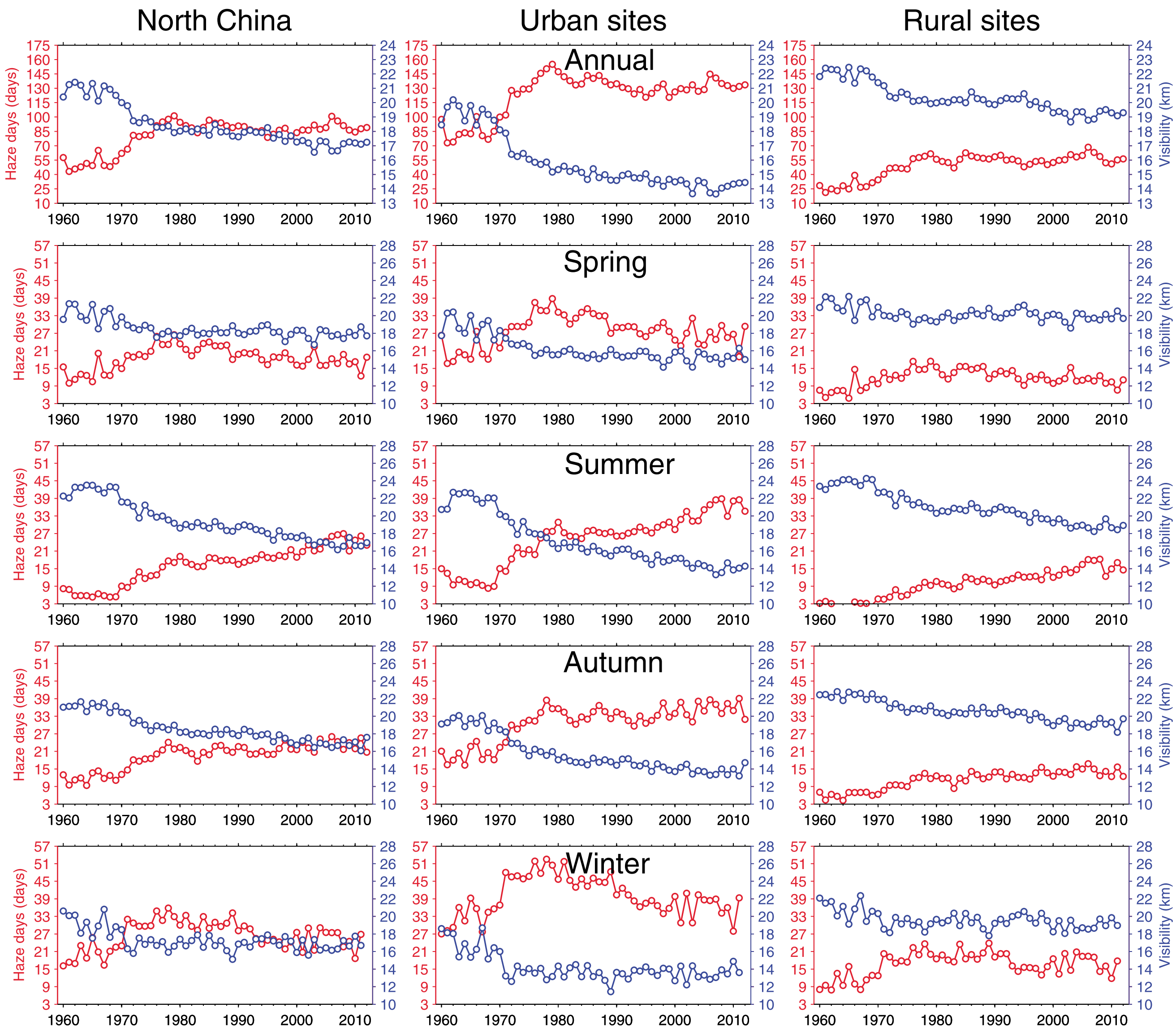

Figure 4. Annual and seasonal evolutions of the number of haze days (red line, days) and visibility (blue line, km) averaged over (left column) North China as well as (middle column) urban and (right column) rural sites from 1960 to 2012.

The long-term variations in the number of haze days in boreal summer and autumn are quite different from the variations in winter and spring over North China, and both present significantly increasing trends from 1960 to 2012, with a linear trend of 3.8 d/decade for summer and 2.4 d/decade for autumn. These

Table 2. Average Climate Values of Haze Days During Different Periods in North China as Well as for Urban and Rural Sites[a]

	North China			Urban Sites			Rural Sites		
	1960–2011	1960s	2000s	1960–2011	1960s	2000s	1960–2011	1960s	2000s
Annual	80.6	51.5	89.7	123.1	83.6	132.5	49.3	27.8	58.4
Spring	18.5	13.5	17.6	27.7	20.9	26.1	11.8	8.1	11.4
Summer	16.1	6.2	23.1	24.8	10.6	33.9	9.7	2.9	15.1
Autumn	19.5	11.9	23.3	30.7	19.6	35.6	11.2	6.2	14.3
Winter	26.5	19.9	25.7	39.9	32.5	36.9	16.6	10.6	17.6

[a]Units: days per year.

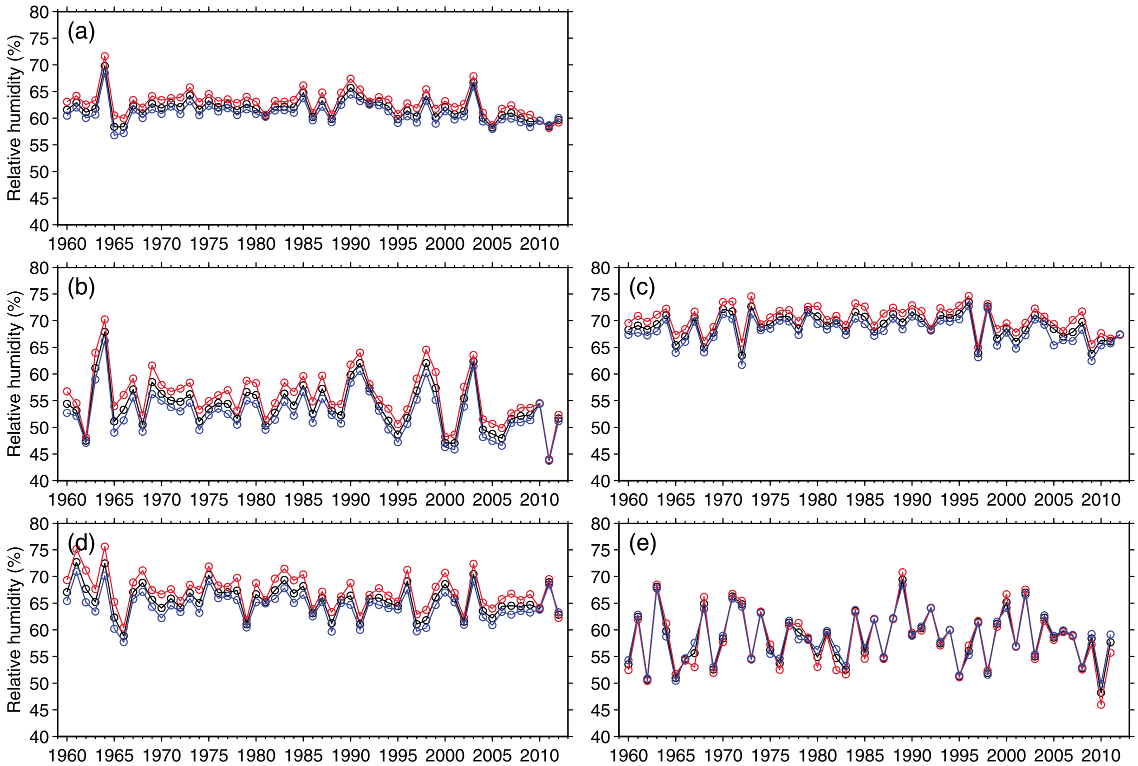

Figure 5. Long-term variations of the near-surface relative humidity from 1960 to 2012 for North China (black line), urban sites (red line), and rural sites (blue line). (a) Annual, (b) spring, (c) summer, (d) autumn, and (e) winter. Units: %.

increasing trends are relatively much larger for the urban regions than for the rural regions, with the trend of 5.2 d/decade and 3.2 d/decade in urban sites for summer and autumn, respectively. The corresponding increasing trends in rural sites are 2.8 d/decade in summer and 1.8 d/decade in autumn. In reality, this difference between the urban and rural regions is primarily a result of the relatively steeper increasing trends in urban regions than in rural sites in the 1970s. The stable increasing trends in the number of haze days generally correspond to the stable decrease in visibility in North China (in both urban and rural sites) in recent decades. Additionally, the decline of the near-surface relative humidity in recent decades [*Qian et al*., 2007; *Ding and Liu*, 2014] is partly responsible for the relatively smaller number of haze days in 2000s than that in 1980s in these two seasons in this region, which will be deeply discussed in the following. The number of haze days is relatively smaller in boreal summer/autumn than in spring/winter; however, the increasing magnitudes in these two seasons are reported to be relatively much larger in this region. In the urban sites, the haze days increased from 10.6 d/yr in the 1960s to 33.9 d/yr in the 2000s in summer and from 19.6 d/yr to 35.6 d/yr in autumn. Obvious increases have also been identified at the rural sites, from 2.9 d/yr in the 1960s to 15.1 d/yr in the 2000s in summer and from 6.2 d/yr to 14.3 d/yr in the autumn.

Early studies [e.g., *Qian et al*., 2007] have documented that the water vapor in atmosphere may have played important roles in affecting the global and diffuse solar radiation reaching the Earth surface. From this study, we suggest that the variations of relative humidity also show obvious influences in the haze occurrences or visibility variability. Figure 5 presents the long-term variations of the annual and seasonal near-surface relative humidity over North China. No apparent trend is reported before 1980s while relative humidity presents to decrease since the early 1990s for annual and seasonal means. This decrease may be partly responsible for the decadal decline of haze events in North China. For example, the number of haze events in spring in 2000s shows much lower than that in 1980s but with almost same level for the visibility in these two periods. The higher relative humidity in 1980s can easily congregate the aerosol particles in the atmosphere that decline the visibility and increase the number of haze events. Compared with 1980s, the relative humidity in 2000s is reported to decrease by 2.8% in spring over North China. More deep

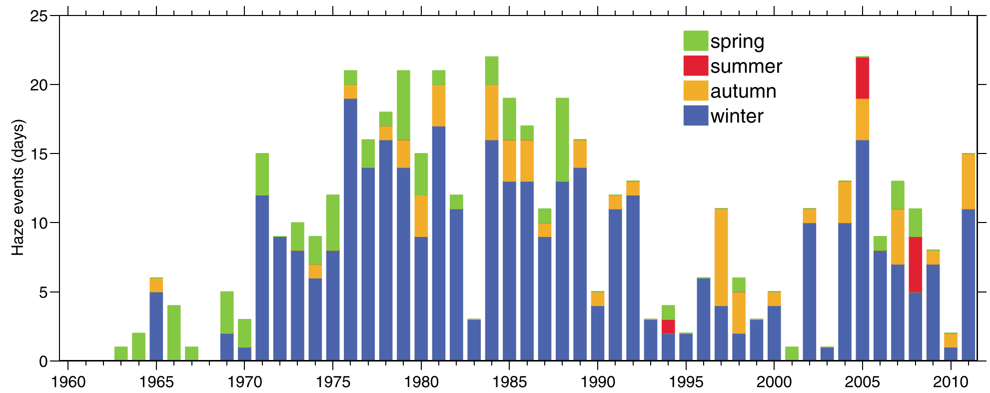

Figure 6. Temporal evolutions of the severe haze events in North China from 1960 to 2011 for the seasons. The severe haze events are defined here as when haze occurred at more than half of the measurement sites. Units: days.

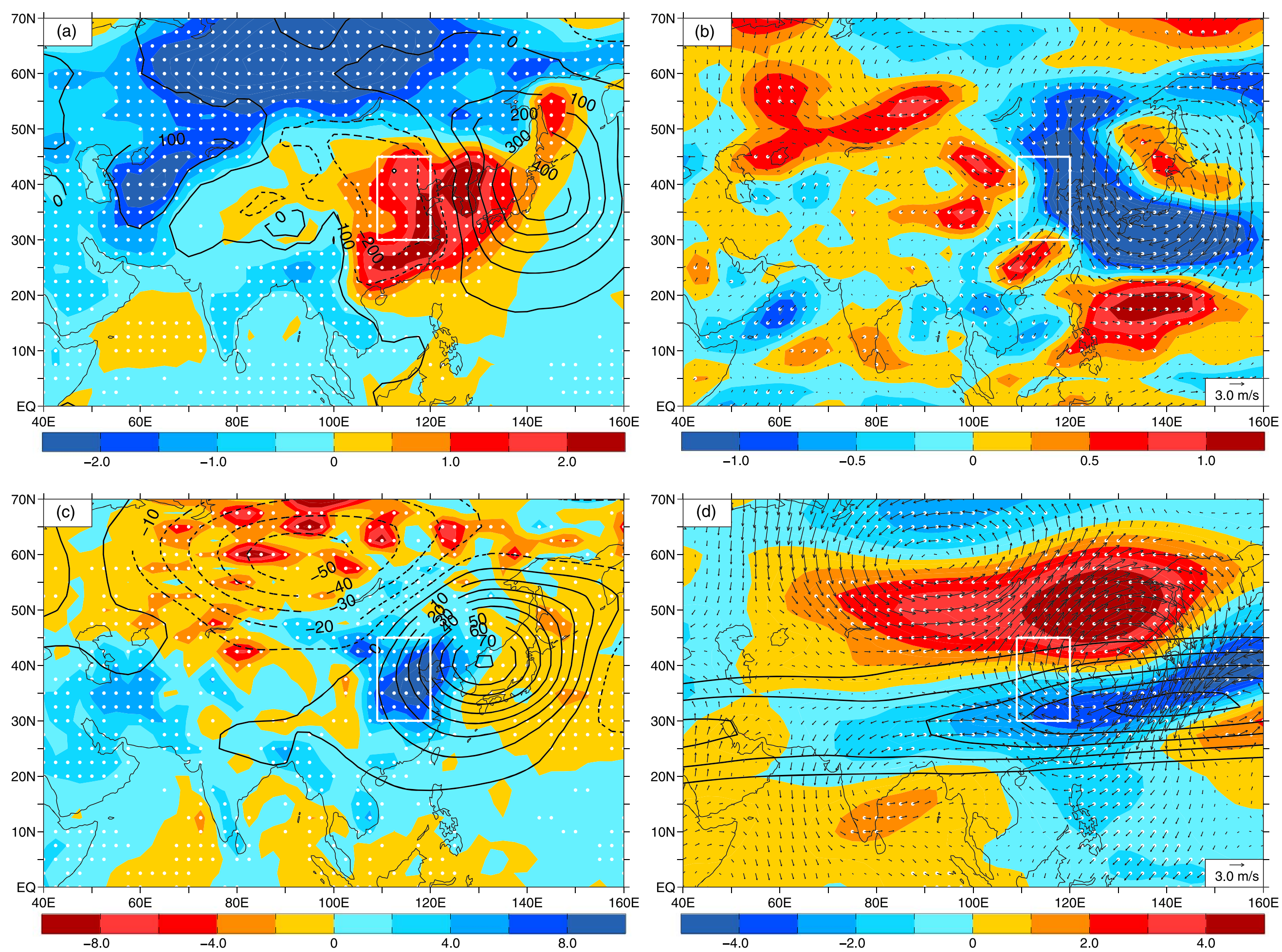

Figure 7. Composite anomalous distributions of (a) sea level pressure (contour; units: Pa) and near-surface air temperature (shading; units: °C); (b) wind vectors (quiver; units: m/s) and wind velocity (shading; units: m/s) in 850 hPa; (c) near-surface relative humidity (shading; units: %) and 500 hPa geopotential height (contour; units: m); and (d) wind vectors (quiver; units: m/s), zonal wind (shading; units: m/s), and western jet stream (contour) in 200 hPa when the severe haze events occurred in boreal winter in North China in the past five decades. The anomalies here are calculated with respect to the period from 1981–2010. The white dots mean that the circulation changes (near-surface air temperature in Figure 7a, wind speed in Figure 7b, near-surface relative humidity in Figure 7c, and zonal wind over 200 hPa in Figure 7d) are significant at the 99% confidence level using *t* test. The box represents the research domain of North China in this study. The analyzed data are derived from the daily NCEP/NCAR reanalysis.

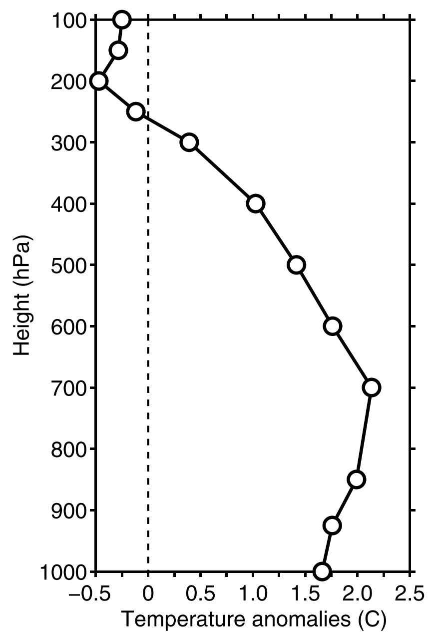

Figure 8. Vertical distribution of air temperature anomalies averaged over North China (110°E–120°E, 30°N–45°N) when the severe haze events occurred from 1960 to 2011. Units: °C.

explanations are still needed in the future work for the effects of water vapor in atmosphere on the variability of visibility or haze.

Briefly, haze days over North China have primarily occurred in boreal winter in the past decades and primarily occur in the early morning (08:00 LT). Over the past five decades, there were relatively few annual haze days in the 1960s; however, the trend shows a steep increase in the 1970s and then remains stable to the present. The long-term variations in the seasonal haze days in this region show some differences from the annual scale and also vary by season. Obvious interdecadal variations in haze days can be observed in spring and winter, relatively low in the 1960s and the 1990s to the 2000s and relatively high in the 1970s and 1980s. However, an increasing trend is strongest in summer and autumn. Similar variations can be observed between urban and rural regions; however, more haze days and relatively larger increasing magnitudes can be observed in urban sites than in rural sites. Furthermore, the number of haze days presents relatively higher in the plain areas than that in the mountain areas, regardless the sites in rural or urban regions (figure not shown). Thus, we suggest that the local emissions of air pollutants should be mainly responsible for the haze occurrences in this region, especially in the urban region.

4. Meteorological Conditions for Severe Haze Events

Early studies have revealed possible atmospheric backgrounds for the haze occurrences in China, although the majority of these studies are limited [e.g., *Zhang et al.*, 2014]. Few studies appear relevant to the associated meteorological conditions from a climatic perspective thus far, which is one of the main targets of this study.

In general, haze occurs largely because of local emissions and region transports, having great effects on society, the ecosystem, and human health. Thus, this study explores the possible meteorological conditions in place when the large-scale severe haze events occurred in North China in the past decades. A severe haze event (SHE) is defined here as occurring when more than half of the measurement sites report haze at a certain time. Figure 6 shows the temporal evolutions of SHEs in North China from 1960 to 2011 for the four seasons. Clearly, the SHEs in North China occurred primarily during boreal winter, showing obvious interdecadal variation, relatively low in the 1960s and relatively high in the 1970s–1980s, then decreasing in the 1990s and increasing since the early 2000s. SHEs in boreal summer mainly occurred in the years 1994, 2005, and 2008. The statistical results indicate that 491 SHEs occurred over North China in the past five decades, and the majority of these events occurred during boreal winter (365 days), accounting for approximately 74% of the SHEs. In the spring, 61 events occurred and 56 occurred in the autumn. The fewest events are in boreal summer, only 9 days. Thus, the following section focuses primarily on the meteorological conditions of SHEs in boreal winter.

Figure 7 depicts the composite distributions of anomalous sea level pressure, near-surface air temperature, winds at low (850 hPa) and high (200 hPa) levels, near-surface relative humidity, and geopotential height (500 hPa) when the SHEs occurred in the winter over North China from 1960 to 2011. These anomalies are calculated with respect to the period from 1981 to 2010. In the lower troposphere (Figure 7a), mainland China is dominated by an anomalous low sea level pressure and a high anomaly over the adjacent ocean

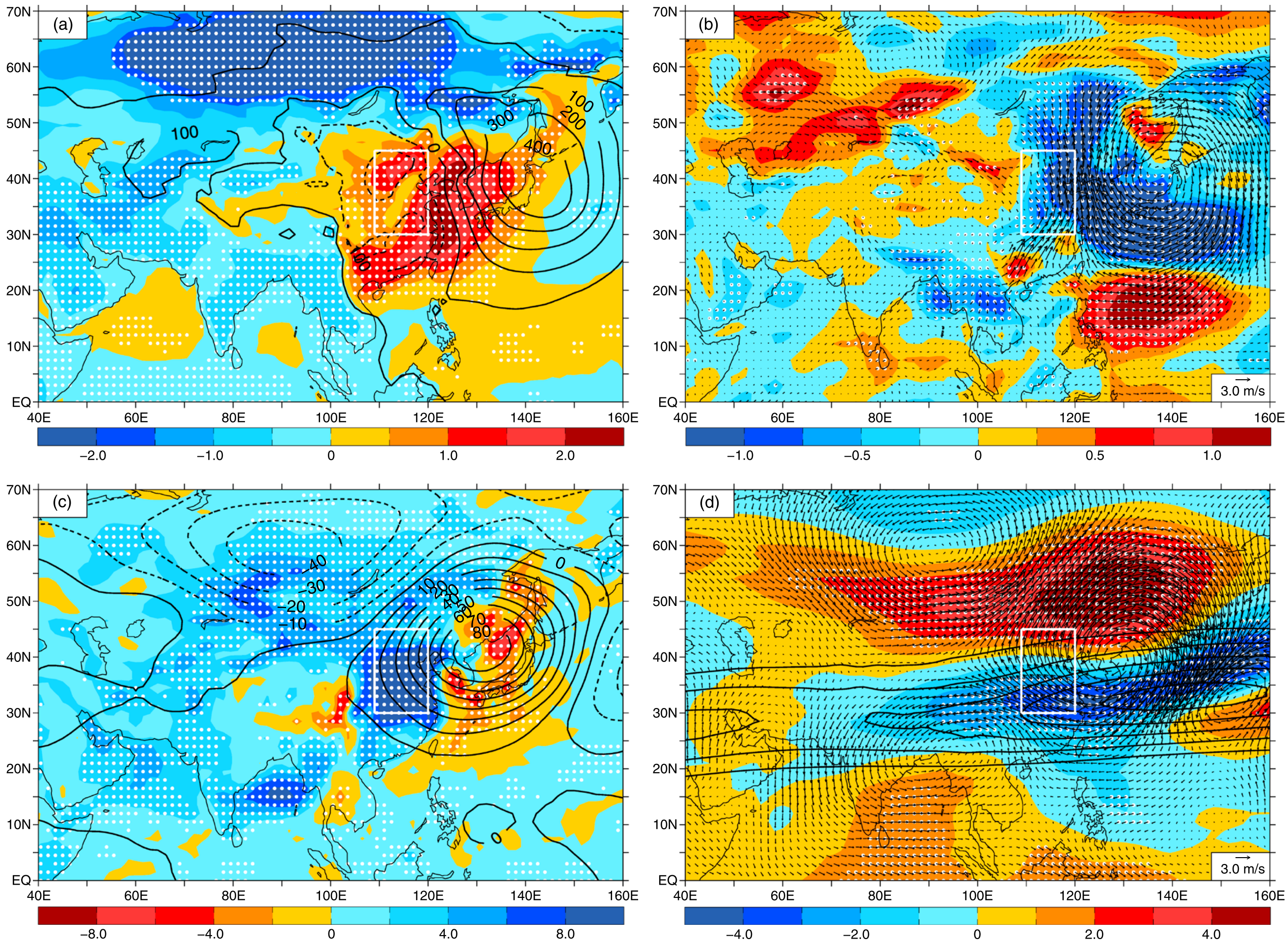

Figure 9. Same as Figure 7; however, the analyses are based on the ERA-Interim reanalysis data for the severe haze events from 1979 to 2011. Note that the relative humidity displayed here is from 925 hPa level.

to the east of the coast, suggesting the weakness of the northerly winds from the high latitudes. Accordingly, the region of North China is under the influence of the southerly anomalies (Figure 7b), resulting in a decline in wind velocity (Figure 7b) and an increase in air temperature (Figure 7a) in the lower troposphere. Because of the weakened northerly winds over eastern China, warm and humid airflows are easily transported into the northern regions of China, creating favorable moisture conditions for a haze occurrence (Figure 7c). In the middle level of 500 hPa, East Asia is mainly dominated by an anomalous high (Figure 7c), implying the weakness of the East Asian trough during haze occurrences. Weakening of the East Asian winter monsoon system [e.g., *Niu et al.*, 2010; *He*, 2013; *Wang and He*, 2013] appears to be responsible for these changes, and its associated weakened circulation brings less cold and dry air to the region, reduces wind speed, and favors the formation and maintenance of haze.

As described above, severe haze events generally result from the effects of both dynamic and thermodynamic factors. On the one hand, the anomalous low in the lower troposphere in mainland China indicates an increased convergence of the air pollutants in this region. The horizontal pollutant transport is further hampered by the weakness of the wind velocity at the near surface. Additionally, the anomalous high in the middle troposphere in this region compromises the development of convection activity, favorable for the congregation of the haze particles at low levels. Furthermore, the East Asian jet stream shifted northward (Figure 7d), suggesting more cold activity occurring in high latitudes and less in the northern region of China. This further enhances the pollutant convergence for the haze occurrence. On the other hand, increased warm and humid airflows sourced from the south are transported into the northern region of China, providing enough moisture for the haze. The near-surface air temperature also increases

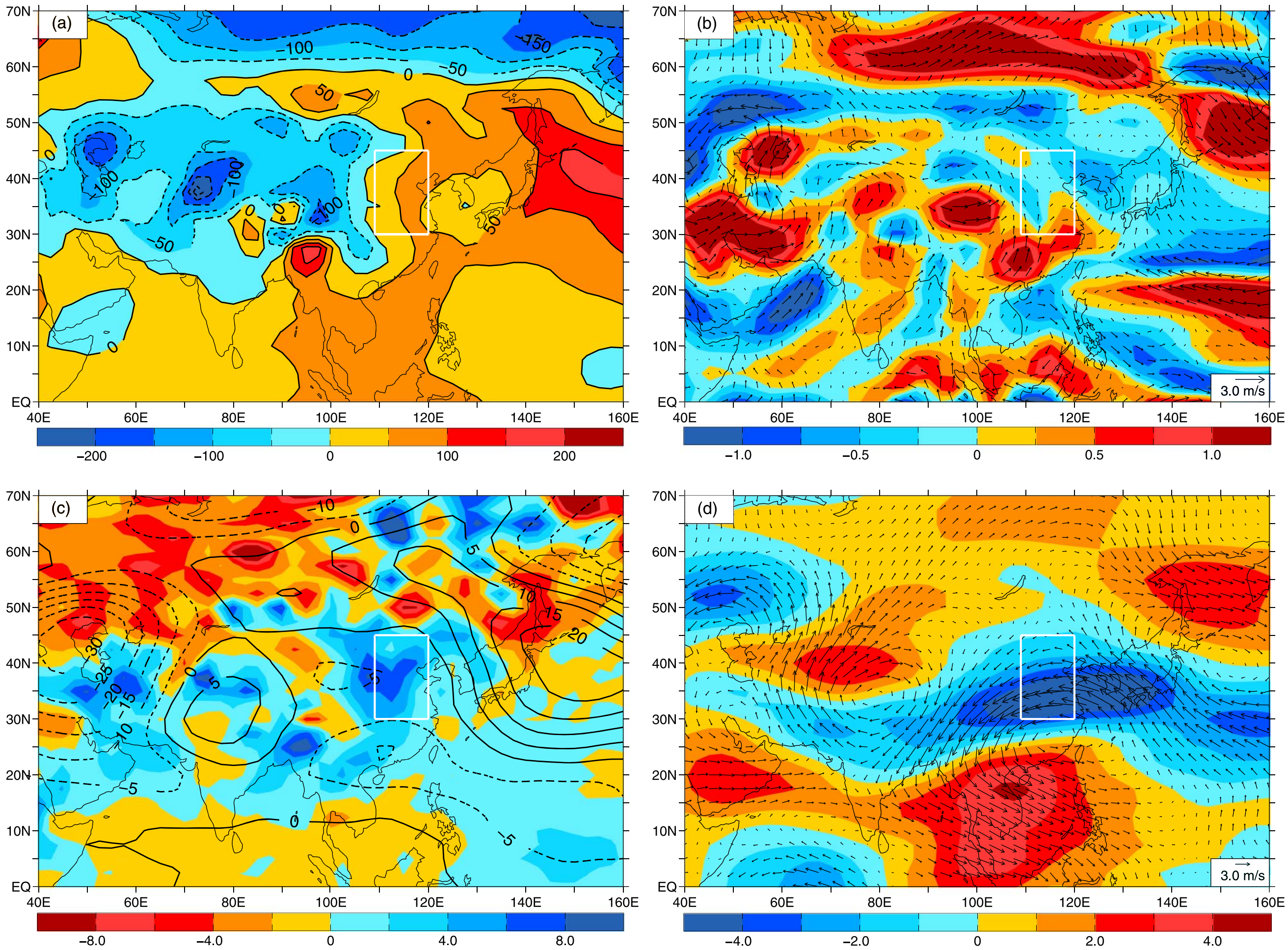

Figure 10. Composite difference distributions of the boreal winter atmospheric circulations for the period 1984–1992 with respect to 1993–2001. (a) Sea level pressure (units: Pa), (b) wind vectors (quiver; units: m/s), wind velocity (shading; units: m/s) in 850 hPa, (c) near-surface relative humidity (shading; units: %), 500 hPa geopotential height (contour; units: m), and (d) wind vectors (quiver; units: m/s) and zonal wind (shading; units: m/s) in 200 hPa. The box represents the research domain of North China in this study. The analyzed data are derived from the monthly NCEP/NCAR reanalysis.

because of the weak northerly winds (Figure 7a). From another perspective, the air temperature further increases partly because of the aerosol absorption and scattering of solar radiation when the haze occurs. We calculated the anomalies of the vertical air temperature differences between 1000 hPa and 850 hPa (T1000 minus T850) for the severe haze events, and the results indicated that the northern regions of China are influenced by the negative anomalies of the temperature difference (figure not shown). This suggests a more rapid increase in the air temperature at 850 hPa than at 1000 hPa, resulting in an anomalous inversion in the lower troposphere (Figure 8) that can increase the stability of the atmospheric stratification at the boundary layer. This anomalous inversion can suppress the vertical transport of the aerosol particles that easily results in haze events; inversely, the increased aerosol loading can further strengthen the inversion of atmosphere. All of these dynamic and thermodynamic anomalies provide a favorable background for the maintenance and development of haze in this region.

To confirm the robustness of the atmospheric circulations linked to the severe haze events in North China, we repeated the above analysis using the ERA-Interim reanalysis, obtaining identical results (Figure 9).

As indicated in Figure 6, the occurrences of the boreal winter severe haze events in North China have undergone obvious interdecadal variations over the past decades, relatively high in the 1970s–1980s and 2000s and relatively low in the 1990s. In addition, more haze events occurred in the 1970s–1980s than in the 2000s. These obvious decadal changes of severe haze events are closely associated with decadal variations in the atmospheric circulation for these periods (Figures 10 and 11). Figure 10 shows the spatial

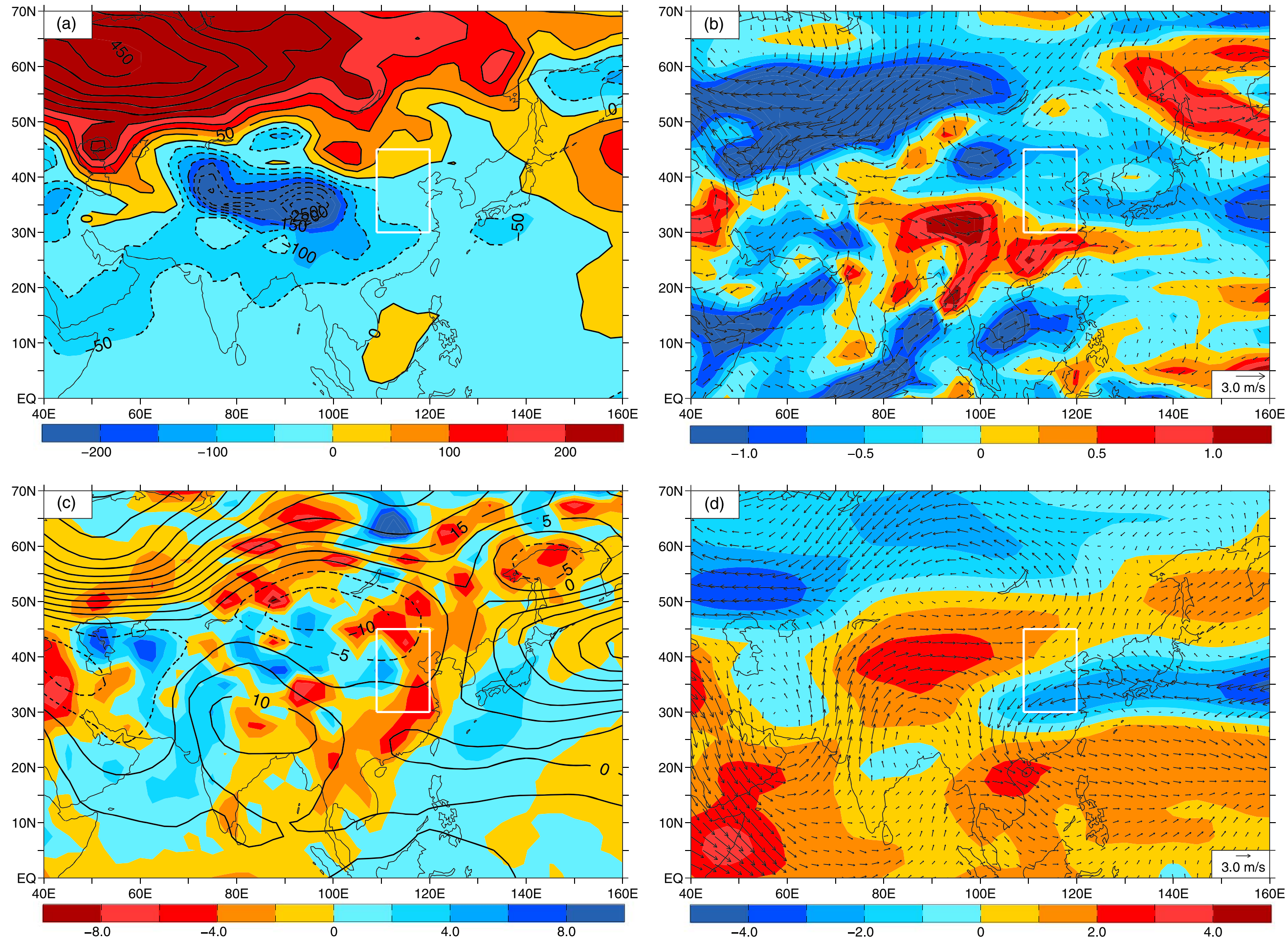

Figure 11. Same as Figure 10 but for the period 2002–2010 with respect to 1993–2001.

patterns of the boreal winter atmospheric circulation differences for the period of 1984–1992 with respect to 1993–2001. Clearly, in the lower troposphere, mainland Asia is mainly dominated by an abnormal low and an abnormal high over its adjacent ocean. The northerly winds over East Asia were much weaker from 1984 to 1992 than from 1993 to 2001, and the southerly anomalies prevailing over this region resulted in the increase in moisture. Additionally, the wind speed in the lower troposphere was much weaker in 1984–1992 over North China than in 1993–2001. An abnormal high is shown over East Asia in the midtroposphere, indicating a much weaker East Asian trough in 1984–1992 when compared to 1993–2001. Furthermore, the East Asian jet stream clearly weakened in the high troposphere and shifted northward in 1984–1992 compared with 1993–2001, implying more stable atmospheric stratification over North China in 1984–1992 than in 1993–2001. These atmospheric circulation anomalies display patterns quite similar to those of the severe haze events that occurred over the past five decades (Figure 7). This indicates that the high occurrences of severe haze events over North China in 1984–1992 were closely linked to the decadal changes of the associated atmospheric circulations, with relatively weaker wind speeds and increased moisture in the lower troposphere, a relatively weaker East Asian trough in the midtroposphere, and a more northward shift of the East Asian jet stream in the high troposphere compared with 1993–2001.

Similar spatial patterns of the atmospheric circulation anomalies can be observed during 2002–2010 when compared with the years 1984–1992, although relatively weaker signals occurred for some circulations (Figure 11). For example, the increase in the moisture in the lower troposphere appears much weaker over North China in 2002–2010 than in 1984–1992, and some regions of North China even show a decrease in 2002–2010. Additionally, the East Asian jet stream in the high troposphere appears much stronger and more southward in 2002–2010 than in 1984–1992. These changes in atmospheric circulation may be why haze events in the 1970s–1980s were more severe than the events in the 2000s over North China. These analyses were also repeated using the monthly ERA-Interim reanalysis data set in this study, obtaining similar results (figures not shown).

5. Conclusions and Discussions

North China is one of the regions with extremely heavy aerosol loadings, and haze events occur frequently in this region. In the present study, the change characteristics of haze events are explored on different scales for this region from 1960 to 2012 using the daily site-gauged data sets. The results indicate that the haze events in North China primarily occur in boreal winter, accounting for approximately 32.8% of the annual haze occurrences. Haze events in spring and autumn account for 23.0% and 24.2%, respectively. In the summer, relatively few haze days occur, just 16.0 d/yr. Further analysis suggests that because of the influence of human activity and favorable meteorological conditions, the haze events that occur at 08:00 LT in this region account for nearly half of these events. To understand the detailed variations in haze events, an analysis of the long-term variations in haze days was implemented for different seasons in this region as well as for urban and rural areas. Over the past five decades, the annual haze days were relatively few in the 1960s but increased steeply in the 1970s and then remained stable to the present. However, the variations in seasonal haze days indicate some differences from the annual scale, varying with the seasons. The long-term variations in haze days in boreal spring and winter are quite similar to the annual variations, relatively low in the 1960s and the 1990s to 2000s and relatively high in the 1970s and 1980s. However, the variations in summer and autumn are mainly dominated by a clearly increasing stable trend. Additionally, no obvious differences in the haze variations can be observed between the urban and rural regions on the annual or seasonal scales; however, relatively more haze days occurred in urban regions and fewer in rural regions, primarily because of the high aerosol emissions in large cities and the lower emissions in small cities.

The haze days analyzed in this study are calculated from the estimated visibility, which is reported to be underestimated (Figure 2). This underestimation can potentially result in the overestimation of haze days theoretically. However, the result is not according to the further computation. The analyses indicated that the estimated visibility mainly ranges from 0.025 km to 7.07 km for all times and all sites when the haze occurred and the corresponding observed visibility ranges from 0 km to 9.8 km from 1980 to 2012. This means, on the one hand, that the frequency of haze days that calculated from the estimated visibility is definitely equal to the result from the observed visibility according to the definition in this study that the visibility less than 10 km when the haze occurred. On the other hand, the visibility underestimation can potentially cause overestimation of haze severity which should be noted in the future works.

The composite analysis of the associated meteorological conditions suggests that the atmospheric circulation anomalies presented in this study are quite favorable to the maintenance and development of haze over North China. In general, the abnormal low in mainland China and the abnormal high over China's adjacent ocean in the lower troposphere can result in weak northerly flows that reduce wind velocity at the near surface. Furthermore, more warm and humid airflows that provide enough water vapor for the haze occurrence can be transported into the region of North China. The East Asian trough in the midtroposphere is weakened, and the East Asian jet core in the high troposphere moves toward the north, suggesting more cold air activities occurring in high latitudes and fewer over North China. The high anomalies in the midtroposphere over North China also suppress the convection activities that weaken the vertical mixing in the atmosphere. Additionally, the air temperature increases with height below 850 hPa, a benefit for the development of inversion anomalies in the near surface and causing the atmospheric stratification in the boundary layer to become more stable. The interactions of all of these factors have provided a favorable atmospheric background for the haze occurrences in this region over the past decades. Further analysis indicates that the decadal variations of the occurrences of the severe haze events over North China are also closely linked to the decadal changes of the associated atmospheric circulations. On the other hand, it is well known that aerosols could affect general circulations and global climates through the direct and indirect effects [*Zhao et al.*, 2006; *Lau* et al., 2006; *Qian et al.*, 2009]. The high aerosol loadings during the haze days may also generate the circulation patterns that favor the formation and maintenance of the haze events. Thus, a possible interaction is reported between the haze occurrences and the associated circulation changes, but more studies are still needed in the future for the further validation.

Compared with earlier studies, some new insights can be derived from this study. First, the analyses in this study primarily concern the long-term change characteristics of haze days over North China using daily data, unlike some earlier studies that focused on one case [e.g., *Zhang et al*., 2014] or one site [e.g., *Wang et al*., 2014]. Thus, a better understanding of the haze occurrences can be derived from this study. Second, the air in the lower troposphere is actually much more humid when the haze occurs, contrary to our earlier views that the air is generally relatively dry. Third, the idea that the haze occurrences generally occur in conjunction with the development of inversion anomalies in the lower troposphere, primarily derived from case studies [e.g., *Zhang et al*., 2014], is further validated by the climatic perspectives of this study. The most important element of this study is that the movement activity of the East Asian jet stream greatly affects the occurrences of severe haze events over North China.

Some previous studies [e.g., *Liu et al*., 2012; *Li and Wang*, 2013, 2014] have documented that the autumn Arctic Sea ice (ASI) loss has substantially influenced the climate over the northern hemisphere in recent decades, especially over East Asia. The recent shift of the Pacific Decadal Oscillation to a negative phase may be responsible for the changes of the summer precipitation pattern in East China after 2000 [e.g., *Zhu et al*., 2010]. Additionally, the decadal change of the summer North Atlantic Oscillation around the late 1970s can significantly enhanced its connection with summer precipitation over some regions of East Asia [*Sun and Wang*, 2012]. Some studies [*Fan and Wang*, 2004; *Wang and Fan*, 2006] have also revealed that the variations of the Antarctic Oscillation presented significant influences on the East Asian summer monsoon circulation and the climates through a meridional teleconnection pattern. However, the possible linkages between these phenomena and the variations of haze events have not been revealed thus far, which will be the interesting issues in the future works. Recently, a study by *Wang et al*. [2015] have revealed the connection between the autumn ASI and the number of winter haze days in eastern China, and the results indicated that the autumn ASI loss can intensify haze pollution over eastern China via the effect of ASI on the associated atmospheric circulations. Certainly, more studies remain necessary to explore the possible effects from both local and teleconnection phenomena on the haze pollution over China for a better understanding of haze formation and to improve the ability to predict haze.

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