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Characteristics of haze change in China since the twenty-first century

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Abstract. Meteorological observation data from 843 national basic/base stations of the China were used to analyze the spatial and temporal distributions of haze in China. The area where there were more than 30 days of haze annually expanded gradually. The average number of haze days across China from 2001 to 2016 was 22.9d. The number of haze days increased gradually from 2001 to 2004 then declined slightly from 2004 to 2012. In 2013, the number of haze days increased to the highest level but then decreased through 2016. The annual number of haze episodes demonstrated a similar trend to the number of haze days. From 2014 to 2016, the cold air was weaker than in the past 30 years. At the same time, the number of breeze days increased and average wind speed decreased. The meteorological conditions were favorable for the formation of haze in China from 2014 to 2016. However, annual haze days, NO2 and SO2 from the OMI (Ozone Monitoring Instrument) data decreased in the three regions from 2014 to 2016, which implies that the emission control program conducted by the Chinese government was effective.

1. Introduction
The rapid development of the economy and urbanization had led to a high emission of air pollutants in China. The annual haze days in many megacities of China increased [1], while visibility decreased [2]. Many megacities had endured the haze weather for a long time, especially the ones in regions with rapid economic development, such as the Beijing-Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta regions [3]. The occurrence frequency of a sustained haze episode significantly increased [4]. Haze weather with large coverage played a bad role in the atmospheric environment [5,6], human health [7-9] and climate change [10]. Researches had shown that the high concentration of regional fine particles (PM2.5) was the main cause of haze weather [11,12]. The fine particle concentrations were affected by several factors, including the emissions and the meteorological conditions [13-16]. Changes in the number of haze days were closely related to the increase of air pollutant concentrations, which itself is largely influenced by meteorological conditions.

It is of significance to strengthen analysis of temporal and spatial distribution of haze, and discussion of mechanism of haze development. Previous studies on haze in China mostly focused on changing meteorological conditions and concentrations of pollutants in specific processes [17]. Several studies had focused on the long-time trend of haze days in China, and had analyzed the
impacts of meteorological conditions and human activities on variations of haze days [18-20]. These studies indicated that the annual number of haze days in China had increased significantly since the year of 2000. Mostly, the previous studies represented the meteorological conditions using the meteorological factors from weather stations rather than the synoptic systems. In this paper, the temporal and spatial distribution characteristics of haze are analyzed using meteorological data during 2001-2016. The meteorological conditions, including the cold air masses and breeze days, were also analyzed in this paper.

2. Data and methods
The meteorological observation data used in this paper were taken from 843 national basic/base stations of the China Meteorological Administration from 2001 to 2016 (Figure 1). This data includes information on temperature, pressure, visibility, relative humidity, wind speed, wind direction and weather phenomena. Haze days were selected with daily visibility less than 10 km and a relative humidity of 85% [21]. Days with precipitation, blowing snow, blowing sand, floating dust, sandstorms, smoke and other weather with low visibility were excluded. A haze weather process was defined as haze weather lasting for three days, with visibility less than 5 km, and occurring in the majority of regions within three neighboring provinces. Column concentrations of troposphere NO2 and SO2 during 2006-2016 were retrieved by an Ozone Monitoring Instrument (OMI) onboard the NASA EOS/Aura satellite (http://mirador.gsfc.nasa.gov) based on differential optical absorption spectroscopy and a principal component analysis retrieve algorithm, respectively.

3. Results
3.1. Spatial distributions of haze in China
As shown in Figure 2, regions with high mean annual haze days were located in eastern China. Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) were the three most important regions. The Sichuan Basin was also a haze-prone area. In the past 16 years, the area with more than 30 annual haze days showed an expanding trend. In the central China, the annual mean haze days increased rapidly after 2012. In Jiangsu Province, the area with mean annual haze days greater than 100 d was limited to the southwest part of the province from 2001-2004 and then...
expanded to the whole province from 2013-2016. Meanwhile, in most cities of central and northern Henan Province, annual mean haze days exceeded 100 d during 2013-2016 and even exceeded 150 d in some cities.

In BTH and its surrounding areas (Shanxi, Shandong, Henan and Inner Mongolia Provinces), the area with more than 60 mean annual haze days showed an increasing trend, covering the entire central and southern regions during 2013-2016. However, there were significant differences across cities in the peak number of haze days and when it occurred. The peak number of annual mean haze days larger than 150 d in southern Hebei and southern Shanxi occurred during 2005-2008, while occurred in 2013-2016 in northern Henan. In the YRD, the area with annual mean haze days larger than 60 d significantly expanded during 2013-2016. The value in Jiangsu and eastern Anhui was more than 100 d. The annual mean haze days in PRD showed a decreasing trend, with most values less than 30 d. These were significantly lower than those in the BTH and YRD regions. In addition, the annual mean haze days in the Sichuan Basin remained high from 2001-2016, showing little fluctuation. In Northeast China, the area with annual mean haze days larger than 11 d also showed an expanding trend during 2013-2016. The occurrence frequency of haze in Northeast China had significant seasonal variations, with a peak in winter, due in part to biomass burning and coal heating. Meanwhile, the large difference between daytime and nighttime temperatures and the high occurrence frequency of inversion in winter prevented the diffusion of pollutants, providing favorable conditions for the occurrence and development of haze.

Figure 2. Spatial distribution of annual mean haze days in China during 2001-2004 (a), 2005-2008 (b), 2009-2012 (c) and 2013-2016 (d).

3.2. Temporal variations of haze in China
As shown in Figure 3, visibility in winter (15.1 km) was significantly lower than in summer (18.2 km). The mean visibility in summer and winter was approximately 20 and 17 km, respectively, during
2001-2002. The mean visibility in summer and winter slowly decreased during 2003-2013, with values remaining at 16-18 km and 14-16 km, respectively. Since 2013, the seasonal variation of mean visibility was more significant, with small changes in summer and a decreasing trend in winter. The mean visibility in the winter of 2016 was only approximately 13 km. In January 2006, January 2013, February 2014, December 2015 and December 2016, the mean visibility was lower than during other months, with persistent large-scale fog and haze processes occurring. The lowest monthly mean visibility since 2001 occurred in December 2016, with three large-scale persistent fog and haze processes.

The annual mean haze days across China gradually increased from 2001 to 2004, slightly decreased from 2004 to 2012, increased to 26 d in 2013, and slightly decreased from 2014-2016 (Figure 4a). The mean value during 2001-2016 was 22.9 d. From 2001 to 2016, the annual mean haze days in BTH, YRD and PRD regions was higher than the average across China. The values in BTH and YRD regions were significantly higher than those in the PRD region. Specifically, the annual mean haze days in BTH slightly decreased during 2006-2013, slightly increased from 2013 to 2014, decreased to 43 d in 2015, and increased to 44 d in 2016. The annual mean haze days in YRD region, slowly increased from 2010 to 2013 (71 d) and decreased from 2014 to 2016 (52 d). For the city of Beijing, the annual mean haze days remained approximately 80 d during 2001-2006, then increased to 102 d in 2008, which was the peak value from 2001-2016. Another peak value (91 d) of annual mean haze days appeared in 2012-2013. After 2013, the annual mean haze days remained approximately 80 d. Overall, the annual mean haze days in Beijing from 2001-2016 was 85 d.

In 2016, the annual mean haze days in Beijing-Tianjin-Hebei regions was 44 d, increasing by 0.5 d from 2015. The values in the cities of Beijing, Tianjin and Shijiazhuang were 83, 83 and 103 d, respectively. This represents a decrease of 1, 1 and 9 days since 2015, respectively. However, from November to December 2016, the annual mean haze days in the Beijing-Tianjin-Hebei region increased by 5 d since 2015. The values in Beijing and Shijiazhuang increased by 5 d and 16 d, respectively, but the values in Tianjin remained unchanged. Similarly, the annual mean haze days in the Yangtze River Delta region was 52 d in 2016, decreasing by 2.7 d since 2015. The values in Shanghai, Jiangsu, Zhejiang and Anhui Provinces were 60, 115, 33.9 and 58 d, respectively. This represents a decrease of 6, 13.6 and 12.5 d and an increase of 2.6 d since 2015, respectively. In 2016, the annual mean haze days in the Pearl River Delta region was 10.3 d, which is 0.7 fewer d compared to 2015. The value in Guangzhou was 18 d in 2016, decreasing by 7 d since 2015. In 2016, the annual mean haze days in Cheng-Yu and Guanzhong of Shaanxi Province and Changsha-Zhuzhou-Xiangtan of Hunan Province generally exceeded 40 d, and these areas were also known as regions with a high occurrence frequency of haze weather.

In recent years, the haze in central and eastern China demonstrated wide coverage, long duration time, low visibility, and serious pollution. For example, several serious haze processes occurred in China in January 2013, February and October 2014, November-December 2015 and December 2016. The number of haze processes (Figure 4b) showed an increasing trend since the beginning of the twenty-first century, with the peak value of 15 occurring in 2013. The number of haze processes slightly decreased to 11 in 2016, in which 8 processes were moderate or severe. This represents a decrease of 3 processes compared to 2015. However, 6 moderate or severe haze processes occurred during November-December 2016, which represents an increase of 1 process since 2015.

![Figure 3. Monthly mean visibility in China since 2001.](image)
3.3. The variation of meteorological conditions related to haze

Meteorological conditions (wind speed, humidity, and cold air strength) are important factors affecting atmospheric pollutant concentration and visibility. These factors influence the dilution, diffusion, accumulation, removal and spread of pollutants in a variety of ways. The accumulation process of haze usually continued between two successive times cold air. From 2001 to 2016, the annual average numbers of total cold air occurrences, medium and strong cold air occurrences were 17.4, 13.0 and 4.4 occurrences respectively. From 2008 to 2013, the number of total cold air and medium cold air occurrences were all significantly higher than the annual average from 2001-2016. Atmospheric general diffusion conditions were better during 2008-2013 than during the other years from 2001-2016. The occurrences of cold air processes decreased significantly from 2014 to 2016. Atmospheric general diffusion conditions during this period were still relatively poor during 2014-2016. In 2016, the number of cold air processes influencing a wide range of China was 16. It was less than the average values from 2001-2016, but it was more than the mean value during 2013 to 2015. Strong cold air occurred 4 times in 2016, whereas the mean value of occurrences during 2013 to 2015 was 2.6 (Figure 5).

Compared with 2013 to 2015 (Figure 6), the more and stronger cold air activity provided favorable meteorological background for the diffusion of atmospheric pollutants in 2016. According to the distribution of cold air activities in different zones, the cold air activities occurred frequently in zone 1 (northeast), zone 2 (the middle east of Northwest China, BTH and surrounding areas) and zone 3 (YRD, Central China and Southwest China), reaching 21, 19 and 14 occurrences, respectively, which were more than the occurrences from 2013 to 2015 and were more conducive to pollutant diffusion. The number of total cold air activities in zone 4 (PRD) was 13 occurrences, but the occurrences of strong cold air were significantly higher than the occurrences from 2013 to 2015. However, in November and December of 2016, the East Asian winter monsoon was weak, affecting fewer occurrences of cold air in Beijing-Tianjin-Hebei, and in the surrounding areas, the overall intensity was generally weak, the activity path was north facing, and the atmospheric diffusion meteorological condition was poor.

Among all kinds of meteorological elements, wind speed had an important influence on haze concentration by affecting the horizontal transport and diffusion capacity of pollutants. The wind speed usually had a significant clearance effect on haze concentration when it was larger than 3m/s. Taking Beijing area as an example, the correlation between wind speed and PM$_{2.5}$ concentration was 0.27, and it was delayed for one hour to achieve the greatest impact. From 2001 to 2013 (Figure 7), the number of breeze days (daily average wind speed less than 2 m/s) of PRD and YRD varied little, accounting for approximately 140 d and 200 d, respectively. The breeze days of Beijing-Tianjin-Hebei
increased slowly from 2001 to 2013, with a growth rate of approximately 1.5 days/year. The breeze days in these three regions increased much after 2013. The breeze days of Beijing-Tianjin-Hebei in 2015 exceeded 200 d. The increased breeze days played a favorable role in the formation of haze. In 2004, there were maximum values of daily average wind speed in the three regions. From 2004 to 2014, the average wind speed of the Pearl River Delta region significantly declined and showed substantial fluctuations. The values of the Yangtze River Delta and Beijing-Tianjin-Hebei did not change much. From 2014 to 2016, the average wind speed of the Yangtze River Delta and Beijing-Tianjin-Hebei decreased significantly, while the average wind speed in the Pearl River Delta did not vary much. The wind speeds of the Yangtze River Delta and Beijing-Tianjin-Hebei reduced to 1 m/s, the minimum in 16 years, in 2016. Against the backdrop of global warming, from 2014-2016, the cold air was at its weakest during the past 30 years. The weak cold air activities led to an increasing number of breeze days, a declining wind speed and the weak diffusion of air pollutants. All the meteorological conditions were conducive to the frequency formation of severe haze in China.

Studies showed that high concentrations of NO\textsubscript{2} and SO\textsubscript{2} played an important role on the formation of haze. The OMI observation data from 2006 to 2016 was used to analyze the variation characteristics of the column amount of NO\textsubscript{2} and SO\textsubscript{2} in different regions of China. As shown in Figures 8 and 9, the seasonal variation of the column amount of NO\textsubscript{2} and SO\textsubscript{2} was significant in BTH, YRD, and PRD regions. The value was low in the summer and high in the winter. From 2006 to 2013, the column amount of NO\textsubscript{2} and SO\textsubscript{2} in the three regions showed a trend of fluctuating growth. Since the Chinese government implemented the air pollution prevention action projects in 2013, the column amount
showed a decreasing trend. This decrease of NO$_2$ and SO$_2$ reflected the effective implementation of pollution reduction measures.

From 2014 to 2016, the diffusion capacity of air pollutants was consistently poor, and the meteorological conditions were favorable for the formation of haze. Meanwhile, the haze days in the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions decreased significantly, that indicated that the emission reduction measures conducted by the Chinese government were effective.

4. Conclusions

(1) Since 2001, the range across China where there were more than 30 annual haze days expanded gradually. In Beijing-Tianjin-Hebei and the Yangtze River Delta, the range where there were more than 60 and 100 haze days also expanded. In the Pearl River Delta, the range where there were more than 30 annual average haze days declined significantly. The number of haze days in the Sichuan Basin maintained a consistently high level during the past 16 years.

(2) From 2001 to 2016, the annual average number of haze days in China was 22.9. The values gradually increased from 2001 to 2004, then decreased slowly with slight fluctuations from 2004 to 2012. The number increased slightly in 2013, then decreased slightly from 2014 to 2016. The haze weather episodes nationwide reaching the peak in 2013 before declining slightly thereafter.

(3) Meteorological conditions affect haze. The number of breeze days increased and the average wind speed decreased. The meteorological conditions were favorable for the formation of haze, but the number of haze days in the three regions decreased. This decrease in haze days reflected the important role that pollution reduction played in China.

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