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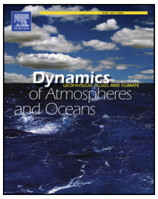

Interannual variation in the number and severity of autumnal haze days in the Beijing–Tianjin–Hebei region and associated atmospheric circulation anomalies

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ABSTRACT

In contrast with the considerable number of studies on the variability of winter haze pollution over eastern China, there have been few studies of autumnal haze in this region. The interannual variability of autumnal (September–November) haze days in the Beijing–Tianjin–Hebei region (AHD_{BTH}) is significantly correlated with the Scandinavia–central Siberia–Western Pacific (SCSWP) teleconnection pattern, a quasi-barotropic atmospheric circulation anomaly. The SCSWP teleconnection pattern may therefore be a useful indicator for forecasting AHD_{BTH}. The positive phase of the SCSWP teleconnection pattern enhances the anomalous anticyclonic circulation centered over the Western Pacific via the southeastward propagating Rossby wave train emanating from Scandinavia. The positive SCSWP teleconnection pattern, together with the northward shift of the East Asian jet stream induced by low-level atmospheric baroclinicity, could provide the favorable local meteorological circumstances (i.e., suppressed cold air activity, higher surface temperatures and low-level atmospheric inversion, and lower planetary boundary layer height and decreased surface wind speed) required to explain the recent increased incidence of AHD_{BTH}.

1. Introduction

Haze is a multi-factorial phenomenon and can be defined by different variables in different fields of study (Yin and Wang, 2016a). In meteorology, haze is defined as dust, smog and water vapor suspended in the atmosphere with a horizontal visibility < 10 km and a relative humidity < 90% (Wu et al., 2007; Liu et al., 2013a). Haze is generally associated with air pollution events (Guo et al., 2014; Xiao et al., 2015; Li et al., 2017) and low visibility (Fu et al., 2014; Zhang et al., 2016) and therefore poses a threat to both human health (Chen et al., 2013; Xu et al., 2013) and vehicular traffic (Wu et al., 2005).

Haze pollution over China has become more severe and frequent since the beginning of the 21st century (Chan and Yao, 2008; Li et al., 2011; Zhang et al., 2012; Luo et al., 2014). As a result of the burning of considerable coal and other fossil fuels in the Beijing–Tianjin–Hebei (BTH) region in winter, this region has the most severe haze pollution in China (Wang et al., 2014b) and severe haze events frequently occur in winter (Che et al., 2009; Zhang et al., 2013; Zhao et al., 2013; Wang et al., 2014c; Zhang et al., 2014; Wang et al., 2015b; Yang et al., 2015b). These haze events are of great concern for both the Chinese government and the academic

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sector (Mu and Zhang, 2014; Yang et al., 2016; Zhou et al., 2017). A case in point is the severe haze episode that occurred in the BTH region in January 2013, with 27 days of heavy air pollution (Wang et al., 2014c), which caused a number of social issues. Because the BTH region is one of the most economically developed regions in China and is at the heart of Chinese politics and culture, the government places a high value on the prevention of air pollution in this area and has formulated various air pollution control regulations and clean air plans to address haze events (Yin et al., 2015a).

Although the anthropogenic discharge of contaminants has played an important part in the sharp increase in haze events over northern China (Wang et al., 2014a; Li et al., 2016b; Wang and Chen, 2016; Wu et al., 2016), atmospheric circulation also has a vital role in the occurrence of haze days. For instance, winter haze events over eastern China are closely tied to the East Asian winter monsoon (Niu et al., 2010; Yin et al., 2015a, b; Li et al., 2016a; Chen et al., 2018) and the Eurasian, eastern Atlantic/western Russia and Western Pacific teleconnection patterns (Yin and Wang, 2016b, 2017; Yin et al., 2017). External forcings, such as the sea surface temperature (SST) (Gao and Li, 2015; Xiao et al., 2015; Yin and Wang, 2016a; Pei et al., 2018; Zhao et al., 2018), Arctic sea ice and the Eurasian snowpack (Wang et al., 2015a; Yin and Wang, 2017; Zou et al., 2017), and the thermal conditions on the Tibetan Plateau (Xu et al., 2016) also exert profound effects on the occurrence of winter haze in China.

A few studies have also investigated autumnal haze pollution and the associated meteorological conditions, although less attention has been paid to autumnal haze days in the BTH region ($\mathrm{AHD_{BTH}}$) than to winter haze events. For example, Gao and Chen (2017) argued that the severe haze pollution over Beijing in October 2016 was affected by the Eurasian teleconnection pattern and the North Pacific Oscillation. Case studies on autumnal haze pollution (Liu et al., 2013b; Yang et al., 2015b) have indicated that the key factors resulting in the formation and evolution of haze episodes are the planetary boundary layer height (PBLH) and the near-surface relative humidity.

According to Chen and Wang (2015), the number of autumnal haze days in North China is climatologically the second highest among the four seasons, and air pollution control and prevention in the BTH region is carried out in the autumn. A better understanding of the $\mathrm{AHD_{BTH}}$-related circulation anomalies could improve the prediction skills for $\mathrm{AHD_{BTH}}$ and provide useful information for the Chinese government to make policy decisions about the year-to-year scheduling of industrial emissions and the treatment of air pollution. The aim of the current research is to unravel the interannual variability of $\mathrm{AHD_{BTH}}$ and the associated anomalous circulation.

The remainder of this paper is structured as follows. The data and methodology are introduced in Section 2. Section 3 explores the circulation anomalies associated with interannual $\mathrm{AHD_{BTH}}$. The discussion and conclusions are given in Section 4.

2. Data and methodology

The datasets used in this study were: (1) monthly PBLH data from the European Centre for Medium-Range Weather Forecasts Reanalysis Interim dataset (Dee et al., 2011) with a horizontal resolution of 1° × 1°; (2) ground-timing observational datasets at 02:00, 08:00, 14:00 and 20:00 Beijing local time from the National Meteorological Information Center of China; and (3) monthly atmospheric data from the National Centers for Environmental Prediction–National Centers for Atmospheric Research Reanalysis dataset (Kalnay et al., 1996) with a horizontal resolution of 2.5° × 2.5°. Data coverage for the PBLH data is from 1979 to 2016 and for the other two datasets from 1960 to 2016.

Autumn was defined as the time period from September to November (September, October and November; SON). The definition of haze days in this study was identical to that of Chen and Wang (2015) and Yin et al. (2017) and was based on the observed relative humidity, visibility and wind speed. In addition, following Zhang et al. (2016), the mean number of haze days ($\overline{\mathrm{NHD}}$) for each $\mathrm{AHD_{BTH}}$ is computed by:

$$\overline{\mathrm{NHD}} = \frac{1}{n}\sum_{i=1}^{n} N \tag{1}$$

where n (here $n = 20$) is the number of synoptic meteorological sites distributed within the BTH region (Fig. 1) and N denotes the number of haze days at a site for each autumn. Because the distribution of these sites is fairly even, the regional mean number of haze days can be used a good representation for the whole BTH region (Zhang et al., 2016).

To focus on the interannual variations, the linear trend in both the time series and in each grid point of the atmospheric data was removed. The 9-year running means were then subtracted from the detrended data to exclude the decadal–interdecadal signals. This approach has been used in previous studies (Hsu and Lin, 2007; Huo et al., 2015; Jin et al., 2016). As a result of the tapering problem for calculating the running mean, the first four years and the last four years of the interdecadal component cannot be calculated directly and therefore are defined as the deviation from the long-term climatological mean (1964–2012). All statistical significance tests are performed based on the two-tailed Student's t test.

To quantify the connection between $\mathrm{AHD_{BTH}}$ and circulation on an interannual timescale, composite analyses (Zhu et al., 2012) were performed. The five positive (1975, 1980, 1987, 1998 and 1999) and five negative (1994, 2002, 2010, 2011 and 2012) $\mathrm{AHD_{BTH}}$ years were selected based on the normalized $\mathrm{AHD_{BTH}}$ (Fig. 2b).