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Climatology of wintertime long-distance transport of surface-layer air masses arriving urban Beijing in 2001–2012

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HIGHLIGHTS

- Multi-year Lagrangian modeling of air masses arriving in Beijing.
- Negative correlation between the BV index and air-quality levels on a multi-timescale.
- Identification of regions with highest priority for mitigating air pollution.

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ABSTRACT

In this study, the FLEXPART-WRF coupled modeling system is used to conduct 12-year Lagrangian modeling over Beijing, China, for the winters of 2001–2012. Based on large trajectory tracking ensembles, the long-range air transport properties, in terms of geographic source regions within the atmospheric planetary boundary layer (PBL) and large-scale ventilation, and its association with air quality levels were quantified from a climatological perspective. The results show the following: (1) The air masses residing in the near-surface layer over Beijing potentially originate from broader atmospheric boundary-layer regions, which cover vast areas with the backward tracking time elapsed. However, atmospheric transport from northeastern China and, to a lesser extent, from the surrounding regions of Beijing is important. (2) The evolution of air quality over Beijing is negatively correlated with large-scale ventilation conditions, particularly at a synoptic timescale. Thus, the simple but robust backward-trajectory ventilation (BV) index defined in this study could facilitate operational forecasting of severe air pollution events. (3) By comparison, the relatively short-range transport occurring over transport timescales of less than 3 days from southern and southeastern Beijing and its surrounding areas plays a vital role in the formation of severe air pollution events during the wintertime. (4) Additionally, an interannual trend analysis suggests that the geographic sources and ventilation conditions also changed, at least over the last decade, corresponding to the strength variability of the winter East Asian monsoon.

1. Introduction

Dramatic air quality degradation occurred with rapidly increasing pollutant emissions due to population growth, rapid industrial development and urbanization in Beijing, the capital of China (e.g., Zhang et al., 2010, 2014; Cao, 2012; Fu et al., 2013; Ding and Liu, 2014; Wu et al., 2015). Due to growing concerns related to air pollution, the alleviation of air-quality problems in Beijing has become a significant issue of concern for the public and the government (Zhang et al., 2010; Cao, 2012).

Since the late 1990s, Beijing has made efforts to implement several vigorous control measures for coal use, heavily polluting vehicles, and industry. These measures successfully resulted in a noticeable decrease in the number of severe pollution days in Beijing, from approximately 200 days in the 1990s to fewer than 80 days in the 2010s (Zhang et al., 2010). However, Beijing and a portion of China have experienced extremely poor air quality, particularly severe haze events with low atmospheric visibility, in recent years (e.g., Cao, 2012; Ding and Liu, 2014). Furthermore, unprecedented air pollution shrouded Beijing City in January 2013, which caused serious problems for resident health and transportation, particularly aviation, and attracted the concern of the scientific community (e.g., Guo et al., 2014; Zhang et al., 2014, 2015; Sun et al., 2014; Tao et al., 2014b; Wang et al., 2014a,b; Zhuang et al.,

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2014; Zheng et al., 2015; Chen and Wang, 2015). The extremely severe air quality events prompted the government to reconsider its policies for emission control and future development in Beijing, including the announcement of new environmental regulations for reducing air pollution and a nation-wide fine-particle-matter-control initiative (Wu et al., 2015).

Extensive studies have been conducted to identify and understand the main factors that contribute to air quality degradation in Beijing, particularly the chemical composition, primary and secondary sources, and formation mechanisms of air pollutants, which were determined using source appointment methods (Hallquist, 2009; Zhang et al., 2013; Huang et al., 2014; Tao et al., 2014a; Zheng et al., 2015; Yang et al., 2015). More recently, Guo et al. (2014) argued that aerosol precursor gases from transportation and industries are essential for the formation of severe haze pollution in Beijing. Nevertheless, due to the complexity of atmospheric chemistry, it is not easy to determine the importance of this effect.

By contrast, the concentrations of near-surface air pollutants over an area at a given time can be regarded as “fingerprints” of transport and the mixing of large amounts of individual air parcels transported from source locations by wind or vertical air currents (e.g., Wang et al., 2004, 2015; Zhu et al., 2011; Oh et al., 2015). Thus, in addition to increasing the amount of air pollutant emissions and secondary production, the formation and evolution of severe air pollution strongly depend on regional transport and synoptic conditions. The transboundary transport of air pollutants is being recognized as a main mechanism that affects air quality over Beijing (e.g., Guo et al., 2014; Sun et al., 2014; Zhang et al., 2014; Yang et al., 2015; Zheng et al., 2015). The main contributions of air pollutants in the series of severe air pollution events in January 2013 in Beijing resulted from outside sources rather than from emission enhancement or local chemical production. Thus, to alleviate severe haze pollution, Beijing must further strengthen its emission-reduction measures, and a similar control should be extended to other regions of eastern China (Sun et al., 2014; Tao et al., 2014b; Yang et al., 2015; Zheng et al., 2015).

Furthermore, the evolution of air pollution is associated with meteorological conditions at multiple timescales. For example, Zhang et al. (2014) argued that stable synoptic meteorological conditions allowed for a more frequent penetration of humid air from the south and led to calm and stable conditions, which explains approximately two thirds of the daily visibility variance over Beijing and is further evidenced by Zhang et al. (2015) and Zheng et al. (2015). At the interannual timescale, Li et al. (2015) stated that the number of fog-haze days during the winter season across Central and Eastern China was related to the East Asian summer monsoon, which determines whether the strengths of the near-surface meteorological circulations are favorable for the accumulation of air pollutants. Zhu et al. (2012) showed that the decadal scale weakening of the East Asian summer monsoon also contributed to greater aerosol concentrations in China. These studies indicated that atmospheric transport conditions are important for maintaining severe air pollution.

Some studies have investigated the long-range sources of pollution in Beijing during heavily polluted events by using chemical transport models (e.g., Zhu et al., 2011; Sun et al., 2014; Han et al., 2015; Zhang et al., 2015) and found that the emission sources of atmospheric aerosol particles in Beijing can be remotely tracked to the southern peripheral greater-scale spatial range of the Hebei, Shandong, Tianjin provinces (Zhu et al., 2011; Sun et al., 2014; Wang et al., 2014c; Wu et al., 2015; Zheng et al., 2015). Notwithstanding the important contributions of these studies, only typical air pollution events were considered and no consensus regarding the exact geographic sources and transport conditions and their relationships with air pollution evolution was obtained, which significantly hinders the efforts of air pollution alleviation initiatives. Details regarding the trans-boundary transport properties of air pollutants over Beijing and their association with regional air quality, particularly from a climatological perspective, remain unclear.

Thus, the identification of primary geographic sources within the atmospheric planetary boundary layer (PBL) and the transport conditions associated with quality evolution are important for developing optimized emission-control strategies. T he main objective of this study is to address the following questions:

1. From which geographical region does the air reaching Beijing originate, particularly from a climatological perspective?
2. Are the variability of transport conditions and the corresponding occurrence of air pollution events over Beijing closely related?
3. Under the background of climate change, what are the regional and long-trending variations of the geographic sources and ventilation conditions, particularly for the last decade?

To answer these questions, multi-year simulations were conducted using the 3-dimensional Lagrangian FLEXPART model, which was coupled with the relatively high-resolution meteorological fields that were produced by mesoscale meteorological modeling in the weather research and forecasting (WRF) mode for the wintertime (Nov–Jan) from 2001 to 2012. Building on the large ensembles of selected backward trajectories, the climatology of spatiotemporal geographic sources were identified in terms of the “density” of the air particles leaving the Beijing urban region and contacting the atmosphere PBL during their backward transport journey. The transport conditions represented by the ventilation index and its association with air pollution, along with their long-term trends, are further explored.

The rest of this paper is organized as follows. Section 2 details the data, trajectory setup, and methods used in this study. Section 3 describes the climatologic perspectives of geographic source regions and ventilation conditions. Section 4 compares the transport properties between the higher and lower visibilities, and Section 5 provides an analysis of long-term trends. Section 6 contains a summary of the study and conclusions.

2. Data, model, and methods

2.1. Meteorological and visibility data

ERA-Interim reanalysis data (Dee et al., 2011) from the European Center for Medium-Range Weather Forecasts (ECMWF) are used as meteorological field inputs to feed the WRF model. The ERA-Interim includes a 4D variation assimilation system and produces a grid resolution of 0.75×0.75 longitude/latitude over 6-hr intervals (at 00, 06, 12 and 18 UTC), with 60 vertical levels from the ground to 0.1 hPa.

The local gauging station data applied in this study include the available 6-h interval observations (atmospheric optical visibility, wind speed and wind direction) obtained during the boreal wintertime (Nov–Jan) from 2001 to 2012, which were obtained from the National Meteorological Center of the China Meteorological Administration observation archives. The data were controlled for quality before being released. The location distribution of the gauge stations within the target region and the region's topography are shown in Fig. 1.

In this study, daily visibility data were obtained from experienced observers that made observations every 6 h at fixed-site monitoring stations in Beijing. The average station observations