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Relay transport of aerosols to Beijing-Tianjin-Hebei region by multi-scale atmospheric circulations

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HIGHLIGHTS

- Penetration of sea-breeze to Beijing was identified by observations.
- Synergistic effects of multi-scale circulations on aerosol pollutant transport were revealed.
- Both observations and modeling well reproduce the relay transport processes of aerosols.

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ABSTRACT

The Beijing-Tianjin-Hebei (BTH) region experiences heavy aerosol pollution, which is found to have close relationships with the synoptic- and local-scale atmospheric circulations. However, how and to what extent these multi-scale circulations interplay to modulate aerosol transport have not been fully understood. To this end, this study comprehensively investigated the impacts of these circulations on aerosol transport in BTH by focusing on an episode occurred on 1 June 2013 through combining both observations and three-dimensional simulations. It was found that during this episode, the Bohai Sea acted as a transfer station, and the high-pressure system over the Yellow Sea and sea-breeze in BTH took turns to affect the transport of aerosols. In the morning, influenced by the high-pressure system, lots of aerosols emitted from Shandong and Jiangsu provinces were first transported to the Bohai Sea. After then, these aerosols were brought to the BTH region in the afternoon through the inland penetration of sea-breeze, significantly exacerbating the air quality in BTH. The inland penetration of sea-breeze could be identified by the sharp changes in ground-based observed temperature, humidity, and wind when the sea-breeze front (SBF) passed by. Combining observations with model outputs, the SBF was found to be able to advance inland more than ~150 km till reaching Beijing. This study has important implications for better understanding the aerosol transport in BTH, and improving the forecast of such aerosol pollution.

1. Introduction

The Beijing-Tianjin-Hebei (BTH) region, located in the North China Plain of the mainland China, covers an area of 216, 000 km^2 with a population exceeding 100 million. Due to the tremendously rapid urbanization and industrialization during the past few decades, the BTH region has become one of the most heavily polluted areas in the world due to the unprecedentedly high aerosol emissions (Chan and Yao, 2008; He et al., 2001; Guo et al., 2011; Huang et al., 2014b; San Martini et al., 2015). This issue regarding deteriorated air quality in BTH has attracted extensive research attention (e.g., R. Zhang et al., 2013; G. Zhang et al., 2014; Quan et al., 2014; Sun et al., 2014; Tang et al., 2016; Wang et al., 2014; Ye et al., 2016). Modeling studies show that the industry, power plants, transportation, residential and agricultural activities all make a contribution to varying extent (e.g., Zhang et al., 2013; Liu et al., 2014; Pui et al., 2014; Guo et al., 2016a). And the formation of secondary aerosols with complex chemical reactions such as aging further complicates this pollution issue (Guo et al., 2014; Han et al.,

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2015; Huang et al., 2014b; Zheng et al., 2015).

In addition to the emission and chemical formation, the air quality in BTH also largely depends on the multi-scale atmospheric circulations (e.g., Chen et al., 2009; Liu et al., 2009; Miao et al., 2015a, 2016; Ye et al., 2016; Zhang et al., 2012). Under certain synoptic-scale circulations, aerosol pollutants emitted from the surrounding provinces (e.g., Shandong and Henan provinces) can be brought to BTH through cross-border transport (e.g., Guo et al., 2013; Li et al., 2013; Wang et al., 2015; Zhang et al., 2015). For example, when a high-pressure system is located to the east of North China Plain, the aerosols emitted from the eastern China (e.g., Shandong province) can be transported to BTH (e.g., Li et al., 2013; Ye et al., 2016; Zhang et al., 2015).

Besides, the local atmospheric circulations also play an important role in modulating the air pollution in the BTH region. With mountains to the north and west of BTH, and the Bohai Sea to the east (Fig. 1), the mountain-plain breeze circulation and sea-breeze circulation develop frequently under favorable synoptic conditions (Hu et al., 2014; Liu et al., 2009; Miao et al., 2015a, 2015b, 2017).

The mountain-plain breeze circulation is generally induced by either the warming of mountain terrains by daytime insolation or the cooling by nocturnal radiation (Banta and Cotton, 1981; Stull, 1988). During the daytime, the upslope breezes occur near the mountainside surface, and a return flow develops simultaneously aloft over the plains. At night, the thermal contrast and the resultant local circulation are reversed. The mountain-plain breeze circulation has been found to affect the planetary boundary layer (PBL) structure and air quality in BTH (Chen et al., 2009; Hu et al., 2014; Miao et al., 2015a). By analyzing model outputs and long-term measurements of automatic weather stations in Beijing, the seasonal variation of mountain-plain breeze circulation in Beijing was unraveled by Miao et al. (2015a): the mountain-plain breeze circulation develops frequently in fall and summer, and is suppressed in spring and winter due to the unfavorable dynamic or thermodynamic conditions.

The sea-breeze circulation, created by the thermal contrast between cool sea and adjacent warm land (Miller, 2003), also plays an important role in the transport of pollutants in BTH (Miao et al., 2015a; Sun et al., 2013). Through numerical simulations, Miao et al. (2015a) demonstrated that the diurnal reversal of land-breeze (offshore wind) and sea-breeze (onshore wind) could cause the pollutants recirculate and accumulated in the BTH region. And several previous modeling studies have illustrated that the sea-breeze originated over the Bohai Sea can penetrate inland more than ~150 km and reach the Beijing area (Liu et al., 2009; Miao et al., 2015a), however, the direct observational evidences for such long a penetration of sea-breeze in BTH have been lacking. Besides, it still remains unclear regarding how and to what extent the sea-breeze circulation could affect the air pollution in the BTH region, partly due to the lack of high-quality surface and PBL observations (Guo et al., 2016b). Thus, to bridge this gap, in this study, we combine surface meteorological observations, wind profiler measurements, and three-dimensional model simulations to investigate the development of sea-breeze of BTH and its impact on air quality.

In addition, although the impacts of the synoptic-scale circulation and local circulations on the transport of aerosol pollutants in BTH have been reported (e.g., Chen et al., 2009; Liu et al., 2009; Zhang et al., 2012; Miao et al., 2015a, 2016, 2017; Ye et al., 2016), respectively, how these multi-scale processes play roles together in the transport pathways of aerosols are rarely comprehensively studied. Another objective of the present study is to investigate the synergistic effect of the synoptic forcing and local atmospheric circulations on the aerosol transport pathways in BTH.

The remainder of this paper is organized as follows. In section 2, the episode selection, datasets, and configurations of the Weather Research and Foresting model coupled with Chemistry (WRF-Chem) (Grell et al., 2005) are described. In section 3, the effects of synoptic forcing and local-scale circulations on the transport of aerosols are examined. Finally, the main findings are summarized in section 4.

2. Data and methods

2.1. Episode description and observations

The aerosol pollution episode selected for this study lasted from 31 May to 1 June 2013. As the true color image and aerosol optical depth (AOD) of MODIS/Terra shown in Fig. S1, there was a thick aerosol layer covering over the south of Hebei province and the west of Shandong province at ~1030 Beijing Time (BJT = UTC + 8 h) on 1 June 2013. And this thick aerosol layer spread over the Bohai Sea where almost no anthropogenic emissions existed (Fig. S2), which could be associated with local-scale or trans-boundary transports of aerosols. The aerosol layer over Bohai Sea could also be found in the true color image of MODIS/Aqua at ~1330 BJT on 1 June 2013 (available at https://worldview.earthdata.nasa.gov). To determine the causes of the aerosol layer over Bohai Sea is also one objective of the present study.

In this study, to examine the regional meteorological condition and the development of local atmospheric circulation, the near-surface meteorological observations collected from 20 surface stations, and the wind profiler measurements (in the northwest of Tianjin city) provided by the China Meteorological Administration (CMA), along with the interim European Centre Medium-Range Weather Forecasts Re-Analysis (ERA-Interim) (Dee et al., 2011) were used. In addition, to validate the simulation results, not only the meteorological observations were used, but also the $PM_{2.5}$ mass concentration measurements collected from 20 air quality stations of the Chinese Ministry of Environmental Protection. As shown in Fig. 1, the air quality stations and meteorological stations used scatter across the eastern China, including five provinces and three municipalities, which provide sufficient data to validate the model outputs.

On 1 June 2013, there was a high-pressure system persisted over the Yellow Sea (Fig. S3), which supported southerly winds passing across the Shandong province toward the BTH region. From 0800 BJT to 2000 BJT, the high-pressure system moved closer toward the continent, leading to the induced near-surface prevailing winds over the BTH region turning from northerly winds at 0800 BJT to southerly winds at 2000 BJT (Fig. S3). Such a weak synoptic condition would favor the development of local atmospheric circulation in BTH on 1 June 2013.

2.2. Three-dimensional simulations

To investigate the effects of synoptic forcing and local-scale circulations on the transport of aerosols in the BTH region, three-dimensional simulations with the WRF-Chem model were conducted. The simulations were initialized at 0800 BJT on 29 May 2013, and ran for 88-h until to 0000 BJT 2 June. The first 64-h were considered as spin-up period, and 2 two-way nested domains (Fig. 1) were employed with horizontal grid spacing of 13.5 and 4.5 km, respectively. Each domain had 48 vertical layers extending from the surface to the 100-hPa level, with 21 layers within 2 km to adequately resolve the PBL structure and local atmospheric circulations. All the model domains used the Yonsei University (YSU) PBL scheme (Hong et al., 2006), Noah land surface scheme (Chen and Dudhia, 2001) coupled with a single layer urban canopy model (Kusaka et al., 2001), RRTMG longwave/shortwave radiation scheme (Iacono et al., 2008), and Lin microphysics scheme (Lin et al., 1983).