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Long-term trends in fog and boundary layer characteristics in Tianjin, China

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ABSTRACT

Long-term trends in fog episodes, vertical variations of atmospheric boundary structure, and air pollutant concentrations during two different heavy fog events in the Tianjin area were analyzed. The total amount of fog has increased since 1980 due to the stability of the boundary layer and an increase of pollutant emissions. The variation in the characteristics of the boundary layer and air pollutant concentrations were significantly different between the two fog processes (fog I and fog II). The onset of fog I was accompanied by a temperature inversion in the low atmosphere, and the average kinetic energy showed a clear diurnal trend and vertical variation, which increased with height. The dissipation of fog I was mainly due to turbulence. However, the atmospheric stratification was not stable in the lower layer before the onset of fog II. The diurnal and vertical changes in kinetic energy were very small, in which turbulent momentum at each measurement height tended to be zero. In the dissipation process of fog II, wind speed increased significantly. Surface $PM_{2.5}$ concentrations decreased, but the ratio of $PM_{2.5}$ to PM_{10} increased from 0.66 to 0.82 until fog I dissipated. However, the concentration of $PM_{2.5}$ did not decrease at the early stage of fog II, but the ratio of $PM_{2.5}$ to PM_{10} $PM_{2.5}/PM_{10}$ decreased to 0.21 when fog II dissipated. This study showed that there was a clear difference in the evolution of pollutant concentration for different pollutants and in different developing stages during the fog events. $PM_{2.5}$ concentration accumulated faster than those of SO_2 and NO_x, and the $PM_{2.5}$ cumulative rate was greater in the mid-term of the fog process.

Introduction

In recent years, frequent dense fogs have been observed in large cities and their surrounding areas. These events have drawn the attention of wider social communities, including public and government agencies. Industrial development, population growth, decreased grass lands, clusters of high-rise buildings and the heat-island effect have contributed to severe fog events in and around the cities. These fog events have a direct impact on transportation and other activities (Fan, Hu, Wang, Wang, & Sun, 2009; Wu, Xie, Wu, Wang, & Zhu, 2009; Zhao, Wang, Li, & Wang, 2010).

Recent studies have shown long-term decreases in fog frequency in certain locations. Canada observed a nationwide decrease in fog events, as indicated by a comparison of 1951–1980 data to 1971–2000 data (Muraca, MacIver, Urquizo, & Auld, 2001). In Sao Paulo, a steady decrease in fog events has been seen on a decadal basis from the 1930s to the 1990s (Hoffman & Nuñez, 2001). However, an increase in dense fog has been seen recently in Beijing, which may be mainly due to increases in the concentration of particulate matter (Wang et al., 2001).

Mechanisms of fog formation and structure can be very complex. Fog and its associated low visibility are related to atmospheric thermal and dynamic processes and chemical reactions among pollutants in the boundary layer (Gultepe et al., 2007; Liu et al., 2010; Liu, Yang, Niu, & Li, 2011; Quan et al., 2013). Urban industries in large, developing cities produce a considerable amount of emissions, which include particulates, nitrogen oxide, and sulfate, etc. (Dzubay et al., 1982; Horvath, 1993, 1995; Hodkinson, 1966). The

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accumulation of nitrogen oxide and sulfur oxides can trigger the formation of lower clouds, fog, and can generate aerosols (Fisak & Rezacova, 2000; Fisak, Rezacova, Elas, & Tesar 2001; Malm, Gebhart, et al., 1994; Malm, Sisler, Huffman, Eldred, & Cahill, 1994b; Tesar, Fisak, & Rezacova, 2002).

The formation of fog occurs under specific weather conditions and is also related to local conditions such as topography and ecological environments. Therefore, fog structure and its evolution can vary greatly. Dynamic, thermodynamic, and micro-physical processes have been analyzed in different locations using field observations (Gultepe et al., 2009; Haeffelin et al., 2010; Pino, Vilà-Guerau de Arellano, Comerón, & Rocadenbosch, 2004; Xu, Bian, & Ding, 2003; Zhang et al., 2005). Fog can often form at relative humidity levels well below 100% due to the high concentrations of fine hygroscopic particulates (Gomez & Smith, 1984). As relative humidity increases, the size of the particulates increases in a non-linear manner, which increases the probability of the formation of fog (Chen et al., 2012; Ogren & Charlson, 1992, Wu et al., 2008; Wu et al., 2010; Wu, Zhang, Zhang, Zhu, & Wang, 2010b). Tianjin has seen high aerosol pollution levels (Bian, Han, Tie, Shun, & Liu, 2007; Han et al., 2009; Tie et al., 2006). However, systemic research on the long-term trends of heavy fog and the structure of the atmospheric boundary layer during a typical fog process are limited in Tianjin. Therefore, studies on the long-term trends of fog and boundary layer characteristics of heavy fog are important in terms of forecasting fog and heavy pollution episodes.

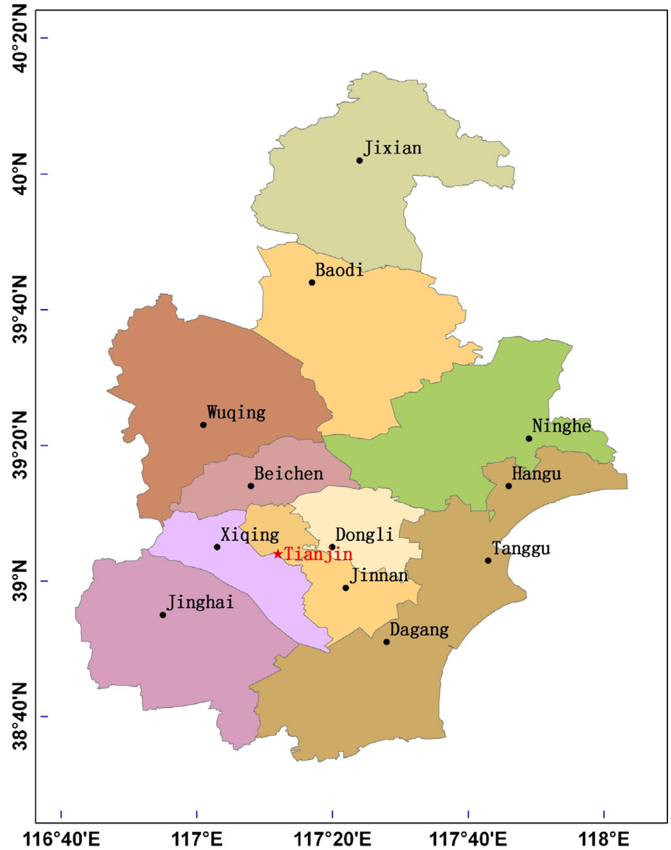

Fig. 1. The locations of the weather stations in Tianjin.

Data and methods

Site description

The data used in this study were obtained with a meteorological tower at a height of 255 m, located at the atmospheric boundary layer observation station in Tianjin (shown in Fig. 1). Tianjin is situated in the eastern part of the North China Plain (NCP), near the Bohai Sea, covering an area of 11,300 km^2 and has a population of eight millions. Due to rapid industrialization and urbanization in recent years, air pollution has become a serious problem in the city. The observation site (the tower, 39°04′29.4″ N, 117°12′20.1″ E) is a mixed residential and traffic area. There are no point sources of pollution near the station.

Measurements and data treatment

The meteorological parameters, including horizontal wind speed, wind direction, relative humidity, and temperature, were measured at 15 platform heights (5, 10, 20, 30, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, and 250 m) every 10 s, and hourly averaged data were used in this study. CAST-3 three-dimensional ultrasonic anemometers (Campbell Scientific, Inc., Logan, UT, USA) were mounted at 40 and 220 m to measure the turbulent fluxes. These meteorological variables are important in the assessment of variations in planetary boundary layer (PBL) (Liu et al., 2012). Atmospheric visibility was measured using Belfort Model 6000 (Belfort Instrument, Baltimore, Maryland, USA). The instruments mentioned above were calibrated according to China Meteorological Administration (CMA) standards (China Meteorological Administration, 2012).

Mass concentrations of O_3, SO_2, and CO at 10 and 40 m and concentrations of NO and NO_2 at 10, 40, and 120 m were continuously measured using Thermo Environmental Instruments (TEom, Thermo co, Franklin, USA). Particulate concentrations were continuously measured using Grimm180 (GRIMM Aerosol Technik, Ainring, Germany).

Mass concentration data of O_3, SO_2, NO, NO_2, CO, and PM were collected every minute, and the results are presented as one-hour averages. However, when 25% or more data points for an hour were missing, that hour was treated as a missing data point.

Meteorological variables were recorded as four synoptic observations per day (02:00, 08:00, 14:00, and 20:00). When one fog event was recorded, it was considered a foggy day.

Results and discussion

Long-term trends in total fog

From 1980 to 2010, there were fewer foggy days over time in Xiqing, Jinnan, Ninghe, Dagang, and Jinghai. An increasing trend was observed in Hangu, Wuqing, Baodi, and Jixian, and slight fluctuations were recorded at urban district (the Meteorological Tower Station), Dongli, Beichen, and Tanggu. The locations of the weather stations at which foggy days decreased are in major urban districts, whereas the locations of the weather stations at which the foggy days increased are in wetlands and mountainous areas within ecologically protected areas.

Fog may appear many times each day, and the duration of a heavy fog may also be different. Thus, the following formula was used to determine total fog:

$$\text{Total fog} = \text{frequency} \times \text{duration}. \qquad (1)$$

The results showed that the total fog increased over time at all stations. The data collected from stations at the urban district, Ninghe, and Hangu are presented in this study as examples.