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Effects of synoptic circulation patterns on air quality in Nanjing and its surrounding areas during 2013–2015

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ABSTRACT

The Yangtze River Delta region is the most active of China's economic regions; however, industrialization and urbanization have seriously affected air quality in the region and air pollution is becoming increasingly serious. Based on the NCEP/NCAR FNL reanalysis data of sea level pressure (SLP) from 2013 to 2015, an objective quantitative method of synoptic circulation classification, T-mode principal component analysis (PCA), was used to analyze the influence of synoptic circulation pattern on air quality in East China. Circulation was divided into nine types: (1) Northwest High Pressure (NWH); (2) Front of Low Pressure (FL); (3) North High Pressure (NH); (4) Northeast High Pressure (NEH); (5) South Low pressure (SL); (6) Weak pressure (Unique); (7) Southwest Low Pressure (SWL); (8) Northeast Low Pressure (NEL); and (9) Low Pressure (L). The air quality in the Nanjing area is discussed in this paper, as well as the relationship between synoptic circulation patterns and local meteorological conditions. The results show that there is a close relationship between synoptic circulation patterns and local meteorological conditions that greatly affects the air quality of the Nanjing area. By the quantitative analysis of the concentrations of five air pollutants ($PM_{2.5}$, CO, NO_2, SO_2 and O_3) under different synoptic circulation types, it was found that circulation type 1 (CT 1, NWH), circulation type 3 (CT 3, NH) and circulation type 4 (CT 4, NEH) were associated with poor air quality; the mean $PM_{2.5}$ concentrations during 2013, 2014 and 2015 were 83.8 μgm^{-3}, 77.6 μgm^{-3} and 78.4 μgm^{-3}, respectively. The local meteorological conditions corresponding to the three circulation types were low temperature and low wind speed. In contrast, circulation type 2 (CT 2, FL) and circulation type 8 (CT 8, NEL), which were associated with better air quality, had opposite local meteorological conditions; the mean $PM_{2.5}$ concentrations were 53.2 μgm^{-3} and 57.7 μgm^{-3}, respectively. This case study shows that the Nanjing region was mainly controlled by CT 1 and CT 3 during the major pollution event in January 2015. The regional transport paths associated with specific circulation types were identified by trajectory analysis in the haze episodes. It was found that two rainfall events played a positive role in improving air quality in the Nanjing area.

1. Introduction

In recent years, the acceleration of industrialization and urbanization has brought rapid economic growth to China. However, most regions of China are exposed to serious air pollution, especially in the North China Plain, the Yangtze River Delta and the Pearl River Delta. Significantly, these three regions have the highest levels of industrialization, urbanization, and air pollution (Chan and Yao, 2008; Wang et al., 2009; Zhang et al., 2010b, 2012b; Zhang and Cao, 2015; Bei et al., 2016; He et al., 2017). Many studies have shown that poor air quality can seriously affect human health (Penner et al., 2001; Zhang et al., 2010a; Liu et al., 2016). Living long-term in a polluted atmosphere, even when the concentration of pollutants is not high, can cause chronic bronchitis, bronchial asthma, emphysema, lung cancer and other diseases. In particular, particulate contamination $PM_{2.5}$ (small particles less than 2.5 μm in diameter) can directly reach the lungs of humans and is the most harmful to human health (Dockery et al., 1993; Pope Iii and Dockery, 2006; Krewski et al., 2009; Huang et al., 2012; Shang et al., 2013). Moreover, air pollution has a significant impact on the weather and climate (Tai et al., 2010; Jacob and Winner, 2009). A large number of particles in the atmosphere makes the air muddy, blocks the sun, and reduces the amount of solar radiation reaching the

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ground (Kamanathan and Carmichael, 2008; Junker and Liousse, 2008). Sulfuric acid leads to acid rain (Du et al., 2017). Because of factory emissions in the city, vehicle emissions can cause a rise in local temperature that results in the "heat island effect" (Sarrat et al., 2006; Crutzen, 2004; Jan et al., 2006). Therefore, accurate air quality assessments, air quality forecasts and a reasonable reduction in air pollution have become increasingly important.

Air pollutants in China's major cities are dominated by particulate matter (Chan and Yao, 2008). Coal combustion, industrial exhaust, and automobile exhaust emissions are the main sources of fine particulate matter and are predominately composed of fine secondary aerosols (Zhang et al., 2009; Li et al., 2010). Optically-scattering aerosols, such as sulfate, organic carbon, nitrate, ammonium and mineral aerosols, constitute most atmospheric aerosols in China (Zhang et al., 2012b). Wang et al. (2014) investigated the spatial and temporal variations of six standard air pollutants in 31 provincial capitals in China from 2013 to 2014 and found that concentrations of pollutants varied in different seasons and different regions. Zhang et al. (2015) studied the status of fine particulate matter ($PM_{2.5}$) in urban China and found that only 25 of the 190 cities could meet the National Ambient Air Quality Standards of China. According to statistics, approximately 83% of the population in China perennially lives with $PM_{2.5}$ concentrations higher than 35 μgm^{-3}, and the death toll reached 1.37 million in 2013 because of excessive inhalation of $PM_{2.5}$ (Liu et al., 2016). The severe pollution in Chinese cities has aroused widespread concern.

Nanjing, the capital of Jiangsu Province in China, is one of the most important cities in the Yangtze River Delta region. Over the past three decades, Nanjing has maintained rapid economic growth and experienced serious air pollution. Because of rapid industrialization and urbanization, the emission of industrial and domestic gas exhaust and vehicle gas exhaust has dramatically increased, with $PM_{2.5}$ and ozone (O_3) as the main pollutants (Chan and Yao, 2008; Wang et al., 2014). These pollutants have increased hazy weather and led to the deterioration of air quality in Nanjing. Therefore, it is necessary to accurately forecast and assess the influence of air pollutants by studying the relationship between atmospheric circulation and the diffusion path of air pollutants in Nanjing.

Factors that affect the scope and intensity of atmospheric pollution are the emission sources (e.g., intensity, spatiotemporal distribution, etc.), meteorological conditions (e.g., temperature, wind direction, wind speed, relative humidity (RH) and the planetary boundary layer height (PBLH)) and the geographical environment (e.g., topography, roughness and cover). Therefore, the control of pollution source emissions and reasonable urban design are positive means to improve air quality. Moreover, meteorological conditions play an important role in the process of pollutant diffusion and advection (Wang et al., 2009; Gao et al., 2011; Liu et al., 2013; Fu et al., 2014; Zhang et al., 2015; Ye et al., 2015; Xu et al., 2016). Demuzere et al. (2009) investigated the impacts of weather and atmospheric circulation on O_3 and PM_{10} levels at a rural mid-latitude site. Levy et al. (2010) studied the effects of atmospheric motion at different scales on air pollutant transport and concluded that the atmospheric motion scales that affected the transport of pollutants varied from season to season. Gao et al. (2011) used the WRF-Chem chemical transport model to study emission controls versus meteorological conditions in the determination of aerosol concentrations in Beijing during the 2008 Olympic Games. The results showed that both emissions reduction and meteorological conditions played important roles in pollutant control and diffusion. Xu et al. (2016) studied the relationship between $PM_{2.5}$ concentration change and meteorological conditions in Shanghai and found that $PM_{2.5}$ concentration in Shanghai was predominantly mass-concentrated in winter and that calm western or southwestern winds (< 1.8 m/s) were the key indicators that affected the $PM_{2.5}$ concentration. Wang et al. (2016) studied the contribution of atmospheric diffusion conditions to the improvement of air quality in China in recent years and showed that good atmospheric diffusion conditions are important for improving air quality.

Circulations have been classified based on sea-level pressure, geopotential height or wind field data (Huth et al., 2008). Because weather effects on air quality are usually associated with the prevailing synoptic-scale circulation background, circulation types are widely used in environmental studies, especially at mid-high latitudes where circulation types are more effective in air quality research (e.g., Jacobeit, 2010; Bei et al., 2013). In general, the study of circulation classification and air quality has seldom been carried out in China. Cheng et al. (2001) found that high O_3 concentrations were often associated with anticyclonic weather conditions and tropical low-pressure systems moving northward to Taiwan. Chen et al. (2008) used the subjective analysis method to study the relationship between the Air Pollution Index (API) and weather conditions in major cities in North China. It was found that high API was associated with a high-pressure system and continuous low-pressure system control. The most serious pollution occurred in front of weak-front pressure fields; Wei et al. (2011) found that the evolution process and different stages of the anti-cyclonic system play a very important role in local air quality. Bei et al. (2016) studied synoptic types and their impacts on wintertime air pollution in the Guanzhong basin in China; the local weather characteristics caused by special terrain were also considered. These studies that explored the relationship between synoptic circulation types and air quality were largely based on case studies and subjective analysis and thus do not represent the historical average meteorological conditions. Therefore, it is important to analyze the relationship between synoptic circulation and pollutant dispersion against the background of long-term climate patterns. Additionally, for an overall assessment of the impact of meteorological conditions on air quality it is necessary to evaluate the effects on the concentrations of several air pollutants, not just on a specific pollutant. This study focused on the relationship between circulation types and air quality in Nanjing and its vicinity. An objective circulation method (i.e., the obliquely rotated T-mode principal component analysis) was first used for the atmospheric circulation classification in this area. The relationships among the synoptic circulation types, the local meteorological conditions and the air quality were analyzed and are discussed based on the observations of several key pollutants from 2013 to 2015 in the Nanjing area.

The remainder of this paper is organized as follows. The data and methods used in this study are introduced in Section 2. The relationships between synoptic circulation types and local meteorological conditions are described in Section 3. The air quality in the Nanjing area under each synoptic circulation type is analyzed in Section 4. In Section 5, the synoptic circulation types and local meteorological conditions during a heavy pollution event in Nanjing in January 2015 are discussed. Conclusions are presented in Section 6.

2. Data and methodology

2.1. Meteorological data

The sea level pressure (SLP) data used for the circulation classification were derived from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) final global forecast system (FNL) reanalysis data that were collected from 2013 to 2015 with a horizontal resolution of $1^\circ \times 1^\circ$ and a range of 19–41°N, 106–132°E. Considering the coverage of the effective data, the 00:00UTC (08:00LT) atmospheric pressure data were selected to determine the daily circulation type among the four valid datasets (00:00UTC, 06:00UTC, 12:00UTC, and 18:00UTC). Fig. 1(a) shows the locations of Nanjing and several of the other main cities in the Yangtze River Delta.

The hourly local meteorological data were derived from the XiaoJiaoChang Observation Station (XJC, 32.0 °N, 118.8 °E) (shown in Fig. 1(b)), which is in the southeast of Nanjing. The meteorology data included pressure, temperature, wind speed, relative humidity and precipitation. These data are used for the international meteorological