Analysis of a Severe Regional Haze-fog-dust Episode over North China in Autumn by Using Multiple Observation Data

Yingxiao Tang^{1,2}, Suqin Han^{1,2*}, Qing Yao^{1,2}, Ziyang Cai^{1,2}, Yulu Qiu³, Jin Feng⁴

¹ Tianjin Environmental Meteorological Center, Tianjin 300074, China

² CMA-NKU Cooperative Laboratory for Atmospheric Environment-Health Research, Tianjin 300074, China

³ Environmental Meteorology Forecast Center of Beijing-Tianjin-Hebei, Beijing 100089, China

⁴ Institute of Urban Meteorology, China Meteorological Administration, Beijing 100089, China

ABSTRACT

The mixing of dust and haze is an important factor in the variation of fine particles. In this study, multiple observation data were used to analyze the characteristics and formation of a haze-fog-dust event that occurred in North China between November 23 and November 30 of 2018. This episode can be roughly divided into two stages, haze-fog and dust, with the transition occurring on November 27. Our analysis shows that stable weather conditions and temperature inversions in North China caused the haze-fog event (November 23–26), during which the PM_{2.5} concentration gradually increased. After November 27, the arrival of cold air accompanied by dust activity rendered meteorological conditions favorable to air quality in the northern part but not the central or southern part of North China. Instead, continuous adverse conditions and the dust backflow, which trapped dust aerosols in the southern part of North China for nearly two days, were responsible for high PM_{2.5} concentrations in Jinan and Zhengzhou after November 27 (146 and 156 $\mu\text{g m}^{-3}$ vs. 114 and 144 $\mu\text{g m}^{-3}$ before November 27, respectively). This study highlights the effect of dust transport on regional environmental pollution during the autumn and the winter.

Keyword: Air pollution; Haze; Dust; Atmospheric aerosols; Fine particles.

INTRODUCTION

Fog and haze are common weather phenomena that dramatically decrease visibility. Moreover, fog and haze are often associated with air pollution events, which greatly threaten public health and impact atmospheric radiation and regional climates (Huebert *et al.*, 2003; Yang *et al.*, 2010; Quan *et al.*, 2011; Chen *et al.*, 2013; Huang *et al.*, 2014; Li *et al.*, 2016a). With the acceleration of urbanization, haze-fog events caused by adverse weather conditions have occurred frequently in the North China Plain, Yangtze River Delta, Sichuan Basin, and Pearl River Delta in recent years (Kaiser and Qian, 2002; Andreae *et al.*, 2008; Fu *et al.*, 2008; Zhang *et al.*, 2012; Zhao *et al.*, 2013). On the other hand, North China is near the Gobi Desert, which is one of the largest deserts in the world (Ginoux *et al.*, 2001; Prospero *et al.*, 2002), and it causes North China to be frequently influenced by dust storms. Simultaneously, the desert dust aerosols can also harm public health and alter the radiation budget (Griffin, 2007; Chan and Yao, 2008; Uno *et al.*, 2009).

Numerous studies have been conducted to investigate haze-fog pollution. These studies showed that high emissions of urban pollutants, the height of the planetary boundary layer (PBL) and relative humidity (RH) were key factors impacting the formation and evolution of haze pollution (Sun *et al.*, 2013; Guo *et al.*, 2014; Han *et al.*, 2014; Zheng *et al.*, 2015; Wang *et al.*, 2016; Liu *et al.*, 2018). By analyzing a severe haze event in Beijing in September 2011, Liu *et al.* (2013) found that the stable conditions at the surface, the decreased PBL height, and the high pollution emissions were crucial to the formation and evolution of this haze episode, with a maximum PM_{2.5} mass concentration of 220 $\mu\text{g m}^{-3}$. A weak East Asian winter monsoon often provides a favorable meteorological background for haze generation. Zhang *et al.* (2014) analyzed the meteorological conditions in a severe haze event over eastern China during January 2013. A weak East Asian winter monsoon resulted in near-surface anomalous inversions, such as weak surface winds and weak vertical shear of horizontal winds, which was conducive to the maintenance and development of a haze-fog event. Dust events can affect downstream meteorological conditions and air quality during the transport process. Zhang *et al.* (2005) revealed that the wind speed increased and RH decreased when a dust storm occurred, and these results were accompanied by increased mixing in the

* Corresponding author.

E-mail address: sq_han@126.com

boundary. From April 23 till 25, 2009, a strong dust storm occurred in Inner Mongolia, which affected China from north to south and affected Guangzhou last. The results showed that the PM_{10} concentration in Guangzhou on dusty days was two times higher than that on non-dusty days (Fan et al., 2013).

The end of haze-fog events is usually due to the effect of cold air, and strong cold air likely accompanied the dust events that occurred (Wang et al., 2014; Wang et al., 2015). During the transport of dust aerosols, the fine particles in the atmosphere can be affected by catalytic and heterogeneous chemical processes (Dentener et al., 1996; Sullivan et al., 2007; Fairlie et al., 2010). Moreover, the mixing of dust and anthropogenic pollutants also affects the downstream areas in dust transport (Sun et al., 2005; Li et al., 2012; Tao et al., 2014a; Tao et al., 2014b). In March 2013, several extreme haze events occurred in Beijing, with dust events occurring in northwestern China; Tao et al. (2014a) divided these haze events into two groups: one group occurred in stagnant weather with a $PM_{2.5}$ concentration below $200 \mu g m^{-3}$ over 1–2 days, and the other group was formed under continuous and intense temperature inversion conditions. The latter events were accompanied by the effects of dust aerosols with a $PM_{2.5}$ concentration exceeding $\sim 400 \mu g m^{-3}$. Moreover, the transported desert dust was further mixed with anthropogenic pollutants as it spread to northern China. Tao et al. (2014b) reported that the dust plumes more than 2 km thick above the haze layers were very important in the formation of the extreme haze pollution event in January 2013. These studies mostly focused on the analysis of a single city and the formation of haze-fog while neglecting the mixture of dust and anthropogenic pollutants in the formation of fine particles. Furthermore, understanding the connection and interactions between dust aerosols and anthropogenic pollutants is crucial to improving regional environmental pollution and

air quality prediction.

Based on joint ground and satellite observations, a haze-fog-dust event over northern China from November 23 till 30, 2018, was analyzed in this study. First, the hourly pollutants and meteorological data in different cities were analyzed to confirm the different episodes in this event. Second, the spatial and temporal distributions of the meteorological conditions, atmospheric vertical structure, and optical properties were analyzed to explain the formation of haze-fog-dust events. Moreover, the effect of pollutant and dust mixtures on the formation of pollution over downstream regions was discussed.

DATA AND METHODS

From November 23 till 30, 2018, a severe regional haze-fog episode occurred over northern China and was followed by airborne dust that affected these regions, including Beijing, Tianjin, Hebei, Henan, and Shandong Provinces. Fig. 1 shows the locations of the major cities investigated in this study.

Air Quality and Meteorological Data

Currently, the Ministry of Ecology and Environment of the People's Republic of China publishes hourly concentrations of PM_{10} , $PM_{2.5}$, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3) in major cities (<http://www.mee.gov.cn/>). The hourly surface meteorological data are available from the China Meteorological Data Service System (<http://data.cma.cn/>). These pollutant concentrations and meteorological data were used to confirm the formation of a haze-fog-dust episode. In this study, we analyzed the hourly air quality and meteorological data from 6 cities: Beijing, Tianjin, Shijiazhuang, Jinan, Qingdao, and Zhengzhou (Fig. 1). Sounding data were used in this study to investigate the variation in vertical meteorological

Fig. 1. The normalized differential vegetation index (NDVI) values in northern China in November 2018 with the black triangles marking the study city locations. The lower NDVI values indicate a lower ground vegetation cover and vice versa.

conditions. The sounding data, which was directly obtained from the University of Wyoming (UWYO) website (<http://weather.uwyo.edu/upperair/sounding.html>), included data such as the vertical variations in temperature and RH detected twice daily at 00:00 and 12:00 UTC in Beijing (39.93°N, 116.28°E), Jinan (36.70°N, 117.55°E), Qingdao (36.06°N, 120.33°E), and Zhengzhou (34.71°N, 113.65°E). In addition, the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data (1.0° × 1.0° resolution) were adopted in this study in the large-scale wind field analysis of the dust event (<https://rda.ucar.edu/datasets/ds083.2/index.html>).

Satellite Data

The Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites is an important sensor that provides many atmospheric parameters by the radiance in 36 spectral bands from 0.4–14.4 μm . The MODIS true-color images provided by Terra and Aqua (satellites covering northern China twice every day at approximately 11:00 and 13:00 local time with 1 km spatial resolution) could show the major regions affected by haze-fog and airborne dust (Engel-Cox *et al.*, 2004; Hsu *et al.*, 2006; Qu *et al.*, 2006). The Collection 6.1 Level 2 MODIS enhanced Deep Blue algorithm (MYD04) provides 10 km aerosol data on the Deep Blue aerosol optical depth (AOD) at 550 nm from November 23 till 30 and was used to analyze the haze and dust pollution over northern China. The Ångström exponent (α) provides information about the particle size. A larger α value indicates the presence of smaller particles in the atmosphere and vice versa. The α value was adopted to distinguish the fine particles and dust aerosols in this study. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud-Aerosol Lidar Pathfinder Satellite Observation (CALIPSO) provides the global vertical structure and optical property observation data for the aerosol and cloud layers (Vaughan *et al.*, 2004; Omar *et al.*, 2009). The CALIPSO algorithms rely on the optical properties of aerosols integrated with the surface type and layer altitude to determine the aerosol subtype, including smoke, dust, polluted dust (dust and smoke), clean and polluted continents, and clean marine. The daily Level 2 5 km Vertical Feature Mask Version 4.20 Product observed by the CALIPSO Lidar was used to study the formation process of regional pollution. Since the observations over northern China are not available on November 27, we only chose the periods of November 23–26 and November 28–29 in this study. The normalized differential vegetation index (NDVI) could accurately reflect the ground vegetation cover, based on the data from the Système Probatoire d’Observation de la Terre (SPOT) VEGETATION instrument and MODIS, which could diagnose the vegetation cover in the dust source area. The NDVI data are retrieved from the Data Center for Resources and Environmental Sciences website (<http://www.resdc.cn>). Lower NDVI values indicate lower ground vegetation cover and vice versa. Fig. 1 shows the NDVI spatial distribution in northern China (30–45°N, 105–125°E). It is clear that in November 2018, the vegetation cover in the northern part of

North China, especially in Inner Mongolia, is relatively low, which provides favorable surface conditions for the production of dust events.

The Definition of Pollution Events

The Chinese Meteorological Administration distinguishes fog and haze based on the visibility and RH, whereby haze is defined as visibility < 10 km and RH < 80% and fog is defined as visibility < 10 km and RH > 90%. When RH is between 80% and 90%, fog and haze are mixing (Tao *et al.*, 2014b; Wang *et al.*, 2015; Han *et al.*, 2016). The Chinese Meteorological Administration distinguishes dust events through the visibility and wind speed. It is difficult to distinguish dust events from haze events solely by using the visibility and wind speed. For example, the criteria for floating dust are defined as visibility < 10 km at a wind speed < 5.4 m s⁻¹. This is similar to the criteria for haze weather. Therefore, the PM_{2.5}/PM₁₀ ratio and PM₁₀ concentration were also simultaneously adopted to distinguish dusty days from haze pollution events in this study. The ratio of the PM_{2.5} concentration to the PM₁₀ concentration was between 0.19 and 0.58 on dusty days in previous studies (Fu *et al.*, 2010; Li *et al.*, 2017; Tian *et al.*, 2018). For the dust event from November 25 till 26, 2018, Ma *et al.* (2019) found that the PM_{2.5}-to-PM₁₀ concentration ratio in the northern regions decreased to 0.41. Therefore, in this study, a dusty day was defined as one with a PM_{2.5}/PM₁₀ ratio < 0.4; moreover, the PM₁₀ concentration was also applied to adjust the duration of the episodes.

RESULT AND DISCUSSION

Pollutant Concentration Variation

Due to its unique topography, the Beijing-Tianjin-Hebei region is prone to haze events. In addition, the dust activities in Inner Mongolia also affect the air quality in this region. In this study, an episode was chosen from November 23 till 30, 2018, including haze-fog and dusty days. Fig. 2 shows the MODIS true-color images captured by Terra and Aqua satellites during this period. The true-color images indicate that on November 23, northern China was relatively clean; however, on November 24, haze clouds appeared from south to north that gradually covered the whole eastern part of North China from November 25 till 26. Simultaneously, dust clouds appeared in central Inner Mongolia on November 26, indicating the appearance of desert dust that spread to the southeast afterward, which coincided with the study of Ma *et al.* (2019). The high PM₁₀ level shown in Fig. S1 also proved the occurrence of the dust event. As shown in Fig. 3, except for Qingdao, the daily PM_{2.5} concentration of each city was higher than 75 $\mu\text{g m}^{-3}$ after November 23. Even in Qingdao, the hourly PM_{2.5} concentration often exceeded 75 $\mu\text{g m}^{-3}$ after November 23. Moreover, the daily PM_{2.5} concentration in Shijiazhuang, Zhengzhou and Tianjin exceeded 115 $\mu\text{g m}^{-3}$ from November 24 till 26. According to Fig. 3, the change in air quality can be divided into two stages, namely, haze-fog and dust in northern China, and the air quality transition occurred on November 27. From November 23 till 26, the change in air quality can be roughly

Fig. 2. Terra and Aqua 1 km MODIS true-color images during the haze-fog-dust events over North China. The black squares mark the haze clouds with a low visibility and a high $\text{PM}_{2.5}$ concentration below; the yellow squares mark the dust clouds with a high PM_{10} concentration below.

divided into two groups: The first group concerns the urban agglomeration represented by Beijing, Tianjin and Shijiazhuang, and the second group concerns the urban agglomeration consisting of Jinan, Qingdao and Zhengzhou.

From November 23 till 26, the hourly $\text{PM}_{2.5}$ concentration in the first group gradually increased, reaching a maximum value exceeding $250 \mu\text{g m}^{-3}$ between the night of November 26 and the early morning of November 27. The high $\text{PM}_{2.5}$ concentration indicated the occurrence of heavy pollution events. In addition, the visibility in the first group was lower than 10 km from November 23 till 26. Hence, this period can be considered a haze process. In the second group, the $\text{PM}_{2.5}$ concentration increased relatively steadily. Thereafter, in Jinan and Qingdao, the $\text{PM}_{2.5}$ concentration gradually increased beginning on the night of November 26, and the maximum value was attained during the daytime. Regardless of the group, a considerable change in the $\text{PM}_{2.5}$ concentration approximately occurred on November 27, which was mainly affected by the transport of desert dust.

To further illustrate the trajectory and impact of dust aerosols, the hourly PM_{10} concentration and the ratio of the $\text{PM}_{2.5}$ concentration to the PM_{10} concentration in each city from November 23 till 30, 2018, are also shown in Fig. 3. The dust event first occurred in central Inner Mongolia. The desert dust affected Beijing and Tianjin, with a maximum

PM_{10} concentration exceeding $600 \mu\text{g m}^{-3}$ in the early morning of November 27, as shown in Fig. 3. During the day of November 27, the desert dust reached Shijiazhuang and Jinan, but there were two peak concentrations in Shijiazhuang; one occurred at midnight before November 26 and the other at 10:00 (BJT) on November 27. The peak at midnight was mainly caused by local emissions during the haze period, while the latter peak was due to the influence of desert dust. From midnight on November 27 till the morning of November 28, desert dust affected Zhengzhou and Qingdao. The dust event first occurred in the middle of Inner Mongolia and then spread southeastward, finally affecting the southern part of North China. Similar to the change in air quality from November 23 till 26, the variation in air quality after November 27 can also be divided into two groups. In Fig. 3, in the second group, after the desert dust reached Shijiazhuang, Jinan, Qingdao, and Zhengzhou, the high PM_{10} concentration ($> 350 \mu\text{g m}^{-3}$) did not decrease as rapidly as that in Beijing and Tianjin (the first group), where it only persisted for approximately 8 hours, whereas in the former areas it remained for longer than 20 hours. This indicates that desert dust remained in the middle and southern part of North China after November 27. Moreover, the hourly $\text{PM}_{2.5}$ concentration in Jinan and Zhengzhou also remained relatively high after November 27. The averaged $\text{PM}_{2.5}$ concentration

Fig. 3. Hourly $\text{PM}_{2.5}$ (black line) and PM_{10} (red line) concentrations and hourly $\text{PM}_{2.5}/\text{PM}_{10}$ ratios (gray shadow) in Beijing, Tianjin, Shijiazhuang, Jinan, Qingdao, and Zhengzhou from November 23 till 30, 2018.

in Jinan and Zhengzhou between November 23 and 26 was approximately 114 and $144 \mu\text{g m}^{-3}$, respectively, which increased to 146 and $156 \mu\text{g m}^{-3}$, respectively, after November 27. It is worth noting that the hourly $\text{PM}_{2.5}$ concentration in Zhengzhou was high, with an average value of approximately $144 \mu\text{g m}^{-3}$ between November 23 and 26, substantially decreased on the evening of November 26 and increased again after November 27. This trend might be attributed to the effect of two desert dust events: one in the mid-northern part of Gansu occurring on November 25 and the other in the middle of Inner Mongolia occurring on November 26 (Ma *et al.*, 2019). These two dust events are shown in Fig. S1. Compared with the other cities, through the variation in the $\text{PM}_{2.5}/\text{PM}_{10}$ concentration ratio, it is further evident that the proportion of fine particles in Jinan and Zhengzhou remained at a high level, sometimes even higher than 0.4 after November 27. Particularly in Zhengzhou, the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio decreased to below 0.4 at 20:00 (BJT) on November 26, indicating that the city was in the dust weather stage at this time. At 15:00 (BJT) on November 27, the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio remained at approximately 0.5 , corresponding to the increased $\text{PM}_{2.5}$ concentration. This likely occurred because the mixing of dust and haze promoted a high fine particle

concentration in places such as Jinan and Zhengzhou. This generated a higher $\text{PM}_{2.5}/\text{PM}_{10}$ ratio than in other cities.

We also analyzed the variation in the NO_2 concentration (Fig. S2). The change in the NO_2 concentration was consistent with the change trend of the $\text{PM}_{2.5}$ concentration in the different cities before November 27, mainly because of local anthropogenic emissions (Tao *et al.*, 2014a). After the dust event on the night of November 26, the NO_2 and $\text{PM}_{2.5}$ concentrations in the various cities showed clear differences. In the first group, the hourly NO_2 concentration exceeded the $\text{PM}_{2.5}$ concentration after November 27, while in the second group, especially in Jinan and Zhengzhou, the $\text{PM}_{2.5}$ concentration considerably increased after November 27, but the NO_2 concentration did not; this result may be due to the influence of dust events, including the presence of fine particles due to dust and the heterogeneous chemistry on the dust surface (Dentener *et al.*, 1996; Bauer *et al.*, 2004; Fairlie *et al.*, 2010). This caused NO_2 to be consumed as a precursor, thus keeping the NO_2 concentration relatively low.

Meteorological Conditions

The variations in air quality are influenced by local emissions and meteorological conditions. Fig. 4 shows the

Fig. 4. Hourly values of the visibility (blue shadow), RH (black line), and wind speed (red line) in Beijing, Tianjin, Shijiazhuang, Jinan, Qingdao, and Zhengzhou from November 23 till 30, 2018.

near-surface meteorological conditions in each city, including the horizontal visibility, RH and wind speed. It is evident from November 23, RH was relatively high in all cities, especially from the evening till the early morning, and RH in most cities exceeded 80%; the high RH provided favorable conditions for the generation of secondary particles (Yang *et al.*, 2015). Correspondingly, the wind speed began to gradually decrease, especially on November 25 and 26, and the lowest wind speed level was attained during the study period; moreover, the visibility was also the lowest at this time, except in Jinan and Qingdao. In Jinan and Qingdao, the wind speed and visibility slightly increased, corresponding to the decrease in $PM_{2.5}$ concentration from November 25 till 26. After November 27, the meteorological conditions exhibited large discrepancies among the different cities as well as the $PM_{2.5}$ and PM_{10} concentrations. Likewise, the meteorological conditions in the cities can be roughly divided into three groups after November 27. The first group is represented by Beijing and Tianjin, which were influenced by northwest winds. In the early morning of November 27, the wind speed increased, and RH suddenly decreased with a shift in the wind direction to the north, indicating that cold

air began to affect these cities. In addition, the visibility began to improve during the daytime of November 27. Moreover, the PM_{10} concentration increased and the $PM_{2.5}$ concentration suddenly decreased, indicating the arrival of desert dust transported by cold air (Fig. 3). In addition, the variation in meteorological conditions in Shijiazhuang was noteworthy. Similar to Beijing and Tianjin, sudden wind speed increases and RH decreases accompanied by the northerlies occurred in the early morning of November 27. However, the visibility did not improve after the cold air invasion. At this time, the high PM_{10} concentration and low $PM_{2.5}/PM_{10}$ ratio indicated that desert dust remained in Shijiazhuang. The second group is represented by Jinan and Qingdao, and the wind direction transitioned from north to east during the dust period. The wind direction changed to the north at 07:00 (BJT) on November 27. Simultaneously, the wind speed increased, which indicated that cold air began to affect Jinan and Qingdao, while RH remained higher than 60% from November 27 till 30 without a significant decrease. Then, the wind direction turned southeastward at 22:00 (BJT) on November 27 in Jinan, and eastward at 01:00 (BJT) on November 28 in Qingdao. At this time, the downtrend of the

PM₁₀ concentration had notably weakened, as shown in Fig. 3. With the eastward transition of the wind direction, dust was transported back by the air flow, which again affected Jinan and Qingdao. This phenomenon is called *dust backflow*, which promotes a high PM₁₀ concentration, and the mixing of dust and haze (Xu et al., 2014; Li et al., 2016b; An et al., 2018). In the third group, represented by Zhengzhou, the weather conditions changed differently from those in the other cities. Before November 26, the meteorological conditions in Zhengzhou were similar to those in the first group, with a high RH and a low wind speed and visibility. At noon on November 26, the wind direction changed to the northwest, which brought cold air accompanied by desert dust from the mid-northern part of Gansu; accordingly, this caused the RH to decrease and the wind speed to increase, corresponding to the decrease in PM_{2.5} concentration. Later, at noon on November 27, the wind direction changed to the northeast, and the wind speed slightly increased. Moreover, the PM₁₀ concentration again increased in the early morning on November 28 (in Fig. 3), indicating the effect of dust backflow on Zhengzhou. The analysis shows that adverse meteorological conditions occurred in North China from November 23 till 26, and cold air accompanied by dust activities on November 27 affected the northern part of North China and caused the meteorological conditions to improve. However, the cold air did not improve the weather conditions in the central and southern parts of North China.

The low surface temperature in autumn and winter slows down the movement of atmospheric molecules, leading to temperature inversion and stable weather conditions. In addition, the high humidity near the ground further aggravates heavy pollution (Liu et al., 2013). Figs. 5 and 6 show the vertical variations in the temperature and RH, respectively, based on the Beijing, Jinan, Qingdao and Zhengzhou sounding station data during the haze-fog-dust event. As shown in Fig. 5, inversions occurred in all areas except in Qingdao from November 24 till 27. There was no distinct inversion layer in Qingdao during the whole study period, which resulted in its diffusion ability in the vertical direction being higher than that in the other places. This absence of an inversion layer partly explained its lower fine particle pollutant concentration than that in other places. The inversion layer in Beijing was first observed at 20:00 on November 24, and did not collapse until November 27. The existence and development of the inversion layer was consistent with the increased PM_{2.5} concentration and the haze event. The inversion layer collapsed at 08:00 on November 27 because of the cold air invasion, and the diffusion conditions were improved. In Jinan, the inversion intensity decreased from 1.8°C 100-m⁻¹ to 1.0°C 100-m⁻¹ after November 26. However, on November 28, the temperature inversion was strengthened with an inversion intensity of approximately 2.4°C 100-m⁻¹ at 08:00 in the surface layer. In Zhengzhou, the inversion layer height was approximately 1000 m with

Fig. 5. Vertical distribution of the temperature (°C) in (a) Beijing (November 24–27, 2018), (b) Jinan (November 26–29, 2018), (c) Qingdao (November 26–29, 2018), and (d) Zhengzhou (November 25–28, 2018).

Fig. 6. Vertical distribution of the relative humidity (%) in (a) Beijing (November 24–27, 2018), (b) Jinan (November 26–29, 2018), (c) Qingdao (November 26–29, 2018), and (d) Zhengzhou (November 25–28, 2018).

an inversion intensity of approximately $1.3^{\circ}\text{C } 100\text{-m}^{-1}$ at 08:00 on November 26 and considerably decreased after November 26 due to the effect of the northwest wind. The near-surface inversion layer was strengthened with the inversion intensity increasing from $1.25^{\circ}\text{C } 100\text{-m}^{-1}$ to $4.7^{\circ}\text{C } 100\text{-m}^{-1}$ at 08:00 on November 28 as a result of the influence of the northeast wind. The occurrence of an inversion layer does not promote the diffusion of pollutants, which compresses pollutants in the vertical direction and thus aggravates pollution. The existence of an inversion layer in Beijing corresponded to the high $\text{PM}_{2.5}$ concentration from November 24 till 26. Moreover, the strengthening of the inversion layer was accompanied by an increase in the $\text{PM}_{2.5}$ concentration on November 28 in Zhengzhou and Jinan. In Fig. 6, the near-ground RH exceeded 60% from November 24 till 26, and it even exceeded 80% some of the time at all stations. At 08:00 on November 26, the high-humidity layer even extended to 1 km above the air in Beijing. However, with the arrival of dust on November 27, which indicated that cold air had arrived, the humidity at each station notably decreased. The high-humidity environment near the ground in Jinan at 08:00 on November 27 corresponded to the high $\text{PM}_{2.5}$ concentration, while the decreased humidity thereafter indicated the occurrence of dust, but the presence of an inversion layer increased the humidity on November 28 with increasing PM_{10} concentration. Due to the influence of the northwest cold air in Zhengzhou on the afternoon of November 26, the humidity near the ground notably decreased at 20:00

on November 26. In addition, the PM_{10} concentration increased and the $\text{PM}_{2.5}$ concentration decreased. However, during the night of November 27, the humidity increased due to the moisture transported by the easterly wind, and the PM_{10} concentration reached its second highest level. At this time, the $\text{PM}_{2.5}$ concentration did not decrease as it did when affected by the northwest wind. This indicated that an increase in humidity is conducive to the generation of fine particles, which in turn affects the $\text{PM}_{2.5}$ concentration near the ground.

Dust Transport and Impact on the Downstream Areas

In Fig. 2, dust appeared in Inner Mongolia on November 26, indicating the occurrence of a dust event. Fig. 7 shows that there were two high-AOD centers in North China on November 26: one in the middle of Inner Mongolia with a strong northwest wind at 850 hPa, and the other in the Beijing-Tianjin-Hebei region with a weak north wind. The maximum AOD in the latter region exceeded 1.0. On November 27, the high-AOD center in central Inner Mongolia moved southeastwardly with the northwest wind at 850 hPa. On November 28, there was an AOD peak with a weak wind field. Moreover, the α value in the two high-AOD centers on November 26 represented contrasting conditions, ranging from 0 to 0.2 in central Inner Mongolia and higher than 1.8 in northern China. The smaller the α value is, the larger the corresponding aerosol particle size is and vice versa. This finding indicates that the high-AOD region in Inner

Fig. 7. (a–c) Aqua MODIS 10 km AOD at 550 nm with the wind field at 850 hPa and (d–f) the Ångström exponent with the wind field at 700 hPa over northern China on November 26, 27, and 28.

Mongolia on November 26 was characterized by a relatively large particle size, while the particles in North China were relatively small. Moreover, it is also clear that the low- α region gradually moved to the southeast under the influence of the northwest wind at 700 hPa (approximately 3 km). Thus, this indicates that the dust clouds gradually moved southward, affecting the downstream area. On November 28, the low- α region (< 0.2) continued to move southeastward, but a high- α region (> 1.8) was encountered in a weak wind field at 700 hPa. The variations in AOD and α indicated a southeastward trajectory of the dust aerosols from November 26 till 28. With the southeastward movement of dust, the air quality was affected in North China from November 27 till 28. The fine aerosol concentration increased in the southern part of North China.

The CALIPSO satellite can be used to better understand the vertical aerosol subtype distribution. The vertical aerosol subtype over northern China from November 23 till 30 is shown in Fig. 8. The polluted air mass was observed as the satellite passed over Shanxi, Hebei, Henan and Shandong Provinces from November 23 till 25. This corresponds to the local haze-fog event. On November 26, a polluted air mass was still observed in Shandong Province, and dust aerosols were observed in Inner Mongolia and northern Hebei Province. Dust aerosols continued to hover over northern China on November 28 and 29, suggesting that the higher $\text{PM}_{2.5}$ concentration in Zhengzhou and Jinan after November 27 was affected by dust aerosols. According to the previous analysis, the variation in the $\text{PM}_{2.5}$ concentration in each city from November 23 till 28 can be roughly divided into two groups, and the difference between the two groups is mainly noticeable after the dust arrives. As shown in Fig. 8, the dust remained in the central and southern parts of North China for nearly two days, which might provide a longer period for the dust to influence fine particle generation.

As shown in Fig. 3, each city experienced different

degrees of haze and dust events. Fig. 9 shows the observed $\text{PM}_{2.5}$ concentration over northern China and the ratio of the observed $\text{PM}_{2.5}$ concentration to the PM_{10} concentration. The range of the high- $\text{PM}_{2.5}$ ($> 150 \mu\text{g m}^{-3}$) area gradually expanded from November 24 till 26, and the $\text{PM}_{2.5}$ concentration in some areas even reached $500 \mu\text{g m}^{-3}$ on November 26. Then, the $\text{PM}_{2.5}$ concentration decreased as cold air and dust moved south of the study area after November 26. From November 23 till 25, according to the distribution variation in the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio, except in Inner Mongolia, most areas of the region attained values higher than 0.5. On November 26, on the one hand, the high- $\text{PM}_{2.5}/\text{PM}_{10}$ range was extended; on the other hand, the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio in Inner Mongolia decreased below 0.3, which corresponded to the occurrence of dust events in Inner Mongolia. Moreover, as time proceeded, the low- $\text{PM}_{2.5}/\text{PM}_{10}$ areas further extended to most of northern China; this change was also related to the movement of dust aerosols. It should be noted that on November 28, although the overall values in northern China decreased below 0.5, simultaneously, in the southern part of North China, the $\text{PM}_{2.5}$ concentration notably increased from November 27 on. This suggests that local fine particles were generated after the dust aerosols moved downstream. As shown in Fig. 9, the effect of dust on the fine particulate matter observed in Jinan and Zhengzhou is not limited to the two urban stations but is observed across the entire southern part of North China.

Discussion

In the previous analysis, the pollution process in North China between November 23 and 30 can be roughly divided into two groups. The difference between the two groups is mainly reflected in the influence of dust. In the first group, the cold air was strong, resulting in a relatively high moving speed of the dust aerosols, which is evidenced by the rapid increase and decrease in the wind speed and PM_{10}

Fig. 8. (a–f) CALIPSO satellite trajectory (blue line) with the colored points marking the study city locations and (g–i) vertical profiles of the classified aerosol subtypes on November 23, 24, 25, 26, 28, and 29, 2018 (N/A = not applicable, 1 = clean marine, 2 = dust, 3 = polluted continental, 4 = clean continental, 5 = polluted dust, and 6 = smoke).

concentration, respectively, in Beijing and Tianjin. In the second group, especially in Jinan and Zhengzhou, the PM_{10} concentration and wind speed did not increase or decrease as fast as those in the first group. Simultaneously, after November 27, the $\text{PM}_{2.5}$ concentration in Jinan and Zhengzhou remained high. This high $\text{PM}_{2.5}$ concentration is mainly caused by dust.

The influence of dust on the $\text{PM}_{2.5}$ concentration in Jinan and Zhengzhou might persist in two ways. First, the dust layer could partly reduce the solar radiation reaching the surface, which caused a temperature inversion to develop, and this in turn weakened the convection and diffusion of the surface $\text{PM}_{2.5}$ concentration (Mohalfi *et al.*, 1998; Ramanathan *et al.*, 2001; Dunion and Velden, 2004; Satheesh and Moorthy, 2005). In Fig. 5, the temperature inversion layer that remained in Jinan and Zhengzhou after November 28 supports this

assumption. Second, when dust is mixed with pollutants, it provides an interface for heterogeneous and catalytic reactions (Dupart *et al.*, 2012; Nie *et al.*, 2012; Nie *et al.*, 2014; Tian *et al.*, 2018). From the variations in the CALIPSO aerosol subtype and hourly PM_{10} concentration, dust is observed to have remained in Jinan and Zhengzhou for more than 20 hours. Li *et al.* (2016b) found that the concentration of different soluble inorganic salt ions (such as nitrate and sulfate) increased in the dust backflow period. Yang *et al.* (2018) found that both remote transmission and secondary formation were the main sources of nitrate during dust storms based on a correlation analysis of nitrate with crustal ions and ammonium. Huang *et al.* (2010) analyzed the components of $\text{PM}_{2.5}$ and the total suspended particulates (TSP) during long-distance dust transmission and mixing

Fig. 9. (a–h) Daily interpolated distributions of the observed $\text{PM}_{2.5}$ concentration and (i–p) $\text{PM}_{2.5}/\text{PM}_{10}$ ratio near the surface over northern China from November 23 till 30, 2018.

with air pollutants in western, northern, and eastern China from March 20 till April 20, 2007. They found that the secondary sulfate concentration during dust storms was higher than the value on non-dusty days, which might be due to the heterogeneous reactions on the dust surface. The mixture of dust and pollutants was carried by the dust backflow, and they remained in Jinan and Zhengzhou for a long period of time. This phenomenon might allow the reaction to be carried out to a greater extent and promote the production of nitrate and sulfate; thus, there was an increase in the $\text{PM}_{2.5}$ concentration. More studies are needed to improve our understanding of the role of dust aerosols in regional heavy pollution over northern China and their interactions in the future. In particular, modeling research could obtain the quantified contribution level of the heterogeneous processes to heavy pollution.

CONCLUSION

This study investigated a regional haze-fog-dust event that occurred in North China from November 23 till November 30 of 2018. The influence and the trajectory of the haze-fog and the dust were evaluated with satellite and

air quality observation data, and the evolution of the haze-fog event was analyzed with surface and vertical meteorological observation data. The effect of dust activity was also concurrently examined.

Based on their variations in air quality between November 23 and November 30, the affected cities of North China can be roughly categorized into two groups for the haze-fog-dust event: Beijing, Tianjin, and Shijiazhuang, and Jinan, Qingdao, and Zhengzhou. In the first group, the $\text{PM}_{2.5}$ concentrations gradually increased from November 23 till November 27, reaching their maximum values during the night of November 26 and the early morning of November 27, after which they decreased with the arrival of cold air. In the second group, no notable elevation was detected in the $\text{PM}_{2.5}$ levels between November 23 and November 27, but they rose considerably after the latter date. The averaged $\text{PM}_{2.5}$ concentrations in Jinan and Zhengzhou were approximately 114 and $144 \mu\text{g m}^{-3}$, respectively, between November 23 and November 26 but increased to 146 and $156 \mu\text{g m}^{-3}$ following November 27. The variation in the PM_{10} concentration and the $\text{PM}_{2.5}/\text{PM}_{10}$ ratio in each city, the distribution of the AOD and Ångström indexes, and the CALIPSO vertical profiles of the classified aerosol subtypes all indicated that the dust observed during

this pollution episode moved southeastward and remained in the central and southern parts of North China for nearly two days.

Our analysis of the meteorological observation data confirms that static and stable weather conditions promote the occurrence and development of haze-fog events, including the episode assessed in this study. Although the intrusion of cold air accompanied by dust on November 27 affected the northern part of North China, increasing the air quality in this area, it did not improve meteorological conditions in the central or southern part. Instead, continuous adverse conditions and the dust backflow trapped dust aerosols in the southern part of this region for nearly two days and were responsible for the high PM_{2.5} concentrations there after November 27.

Adverse meteorological conditions and pollutant emissions are the primary causes of haze-fog events, and cold air typically accompanies the endings of such episodes during autumn and winter. However, the arrival of strong cold air also occasionally results in dust events, which influence the formation of fine particles in downstream areas and lead to an increase in the concentration of this fraction, especially when combined with a dust backflow and persistent adverse conditions. Modeling studies are needed to quantify the role and interactions of dust aerosols in the heavy regional pollution across North China.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.2019.11.0567>

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