Characteristics of Boundary Layer Structure during a Persistent Haze Event in the Central Liaoning City Cluster, Northeast China

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ABSTRACT

The characteristics of boundary layer structure during a persistent regional haze event over the central Liaoning city cluster of Northeast China from 16 to 21 December 2016 were investigated based on the measurements of particulate matter (PM) concentration and the meteorological data within the atmospheric boundary layer (ABL). During the observational period, the maximum hourly mean $PM_{2.5}$ and PM_{10} concentrations in Shenyang, Anshan, Fushun, and Benxi ranged from 276 to 355 μg m^{-3} and from 378 to 442 μg m^{-3}, respectively, and the lowest hourly mean atmospheric visibility (VIS) in different cities ranged from 0.14 to 0.64 km. The central Liaoning city cluster was located in the front of a slowly moving high pressure and was mainly controlled by southerly winds. Wind speed (WS) within the ABL (< 2 km) decreased significantly and WS at 10-m height mostly remained below 2 m s^{-1} during the hazy episodes, which was favorable for the accumulation of air pollutants. A potential temperature inversion layer existed throughout the entire ABL during the earlier hazy episode [from 0500 Local Time (LT) 18 December to 1100 LT 19 December], and then a potential temperature inversion layer developed with the bottom gradually decreased from 900 m to 300 m. Such a stable atmospheric stratification further weakened pollutant dispersion. The atmospheric boundary layer height (ABLH) estimated based on potential temperature profiles was mostly lower than 400 m and varied oppositely with $PM_{2.5}$ in Shenyang. In summary, weak winds due to calm synoptic conditions, strong thermal inversion layer, and shallow atmospheric boundary layer contributed to the formation and development of this haze event. The backward trajectory analysis revealed the sources of air masses and explained the different characteristics of the haze episodes in the four cities.

Key words: haze event, thermal inversion layer, atmospheric boundary layer, Northeast China

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1. Introduction

Haze pollution in China has increased over the past three decades, particularly in city clusters, as a result of the rapidly developing economy, expansion of anthropogenic activities and urbanization (Shao et al., 2006; Fu et al., 2014; Wang et al., 2014a). In recent years, heavy and persistent haze events have been observed in different regions of China (Ji et al., 2012; Liu et al., 2015; Peng et al., 2016), resulting in atmospheric visibility reduction, increased air pollution, and risks to public health (Chan and Yao, 2008; Chen et al., 2012; Che et al., 2014; Zhang et al., 2014; Shen et al., 2015; Tang et al., 2017).

Haze formation is closely related to meteorological

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conditions and high aerosol mass loadings (Wang et al., 2014b). In the northern part of China, heavy air pollution often occurs in the heating season or during periods mainly due to large pollution emissions associated with agricultural residue burning and unfavorable meteorological conditions for pollutant dispersion (Fu et al., 2014; Wang et al., 2014b; Zheng et al., 2015; Chen et al., 2017). Since the heating season begins earlier and lasts longer in Northeast China as compared to most regions in China and is combined with burning of agricultural residues, haze occurs frequently during winter in this region. For example, a heavy and persistent haze event with a maximum $PM_{2.5}$ concentration exceeding 1000 μg m^{-3} occurred during 1–8 November 2015 in Shenyang and profoundly shocked both the public and the government. Several studies have reported that haze pollution in Northeast China is serious (Cui et al., 2015), with an increasing trend in particulate matter (PM) observed at some stations in this region from 2006 to 2014 (Wang et al., 2015c).

Many efforts have been made to identify the meteorological causes of haze events involving the effects of surface meteorological conditions, synoptic patterns, climatic background, and local atmospheric circulation induced by the topography (Chen et al., 2008; Liu et al., 2009; Zhu et al., 2012; Hu et al., 2014, 2016). Zhu et al. (2012) demonstrated that the weakened monsoon circulation of recent decades has made a significant contribution to trapping pollutants over eastern China. The modeling results reported by Miao et al. (2015, 2017) revealed that local atmospheric circulation plays an important role in surface air pollution over the Beijing–Tianjin–Hebei region. In addition, the structure of the atmospheric boundary layer (ABL) is also crucial to the formation and evolution of haze (Wang et al., 2006; Yang et al., 2010; Lu et al., 2011; Tang et al., 2016, Ye et al., 2016). Wu et al. (2009) and Sun et al. (2013) found that the vertical dynamic and thermal variations within the ABL influence pollutant concentrations. Quan et al. (2013) compared the ABL evolution during clear and hazy conditions in Tianjin and considered the possibility of a positive feedback cycle between atmospheric aerosols and lower ABL height, which would induce heavy surface-level pollution in cities. Liu et al. (2015) analyzed ABL characteristics during a typical haze process in January 2014 over the Pearl River Delta region and found that weak wind, low ABL height, and a thermal inversion layer under stable atmospheric conditions were major reasons for haze formation. Hu et al. (2014) investigated the impact of the Loess Plateau on the ABL structure and air quality in the North China Plain (NCP). Based on field measurements, similar studies have also been conducted in other megacities or regions, such as the Beijing–Tianjin–Hebei region (Liao et al., 2014; Wang et al., 2014a), Xi'an in western China (Wang et al., 2016), and eastern China (Li et al., 2015; Peng et al., 2016), but such studies are still very rare in Northeast China (Zhang et al., 2010a, b; Liu et al., 2011). These previous studies have contributed to our understanding of the effects of ABL evolution on the changes in surface air pollution and provide a reference for studies of the interaction of ABL meteorology and aerosols in haze modeling and prediction (Wang et al., 2015a, b).

In this study, the characteristics of ABL structure during a persistent, severe regional haze event over the central Liaoning city cluster during 16–21 December 2016 were analyzed, by using the vertical profiles of ABL meteorological variables and surface PM concentration, combined with horizontal wind fields retrieved from the ECMWF reanalysis data and back trajectory analyses from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model of NOAA (Draxler and Rolph, 2003; Wang et al., 2010). In Section 2, a brief introduction to the study area and details of the data and methods are described. The results and discussion, given in Section 3, mainly address temporal variation in PM concentration and surface meteorological variables, and the horizontal and vertical structure of the boundary layer. Finally, the conclusions of the study are presented in Section 4.

2. Data and methods

2.1 *Description of the study area*

Liaoning Province is an industrial region that has made a substantial contribution to the economic development of Northeast China (Che et al., 2015). Our study focused on the central Liaoning city cluster, which comprises Shenyang, Anshan, Fushun, and Benxi (Fig. 1a). These four cities are located in a heavily populated industrial region of Northeast China (38.43°–43.26°N, 118.53°–125.46°E), a major source area for aerosol pollution originating from a variety of human activities, industrial, and transportation sources (Ma et al., 2012; Zhao et al., 2013a; Che et al., 2015). Particularly in winter, emissions from coal burning for domestic heating are a well-established source of pollution (Zhao et al., 2013b; Che et al., 2015).

2.2 *PM concentrations and surface meteorological parameters*

Large-scale regional haze pollution has been charac-

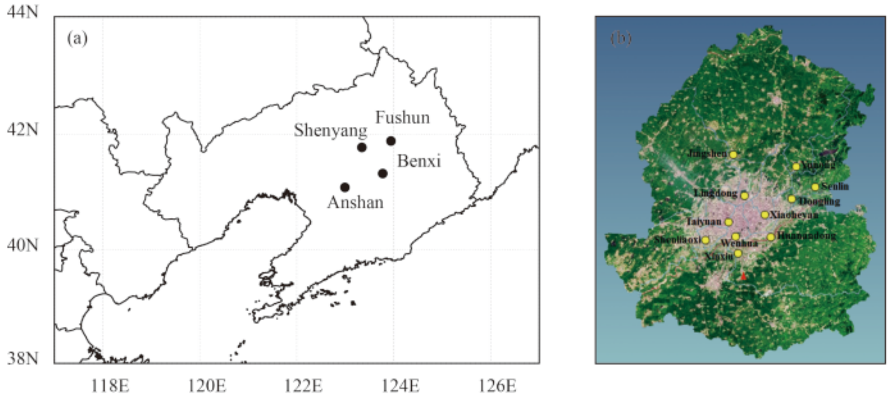

Fig. 1. (a) Geographical locations of four cities in the central Liaoning city cluster of Northeast China, and (b) positions of 11 environmental monitoring stations (yellow circle) and the boundary layer experiment site (red triangle) in Shenyang.

terized by high concentrations of $PM_{2.5}$ in recent years (Wang et al., 2014a). In this study, the hourly mass concentrations of PM_{10} and $PM_{2.5}$ in Shenyang, Anshan, Fushun, and Benxi during a typical haze event from 16 to 21 December 2016 were obtained from the Liaoning real-time air quality monitoring system. There are eleven monitoring stations located in Shenyang, seven in Anshan, and six each in Fushun and Benxi. The ambient real-time monitoring instruments, Models 5030i and 5014i were used to measure the concentrations of $PM_{2.5}$ and PM_{10} at each station, and then the averaged PM data from different stations in each city were used in this study.

The simultaneous hourly mean surface meteorological parameters, i.e., wind speed (WS), wind direction (WD), air temperature (T_a), relative humidity (RH), and atmospheric visibility (VIS), from the national weather stations in the four cities were used to analyze the surface meteorological conditions.

2.3 *Boundary layer structure*

The ECMWF reanalysis data with a spatial resolution of 0.125° × 0.125° were used to retrieve the horizontal flow fields at 10 m above ground level (AGL) over Liaoning from 16 to 21 December 2016. The ECMWF data were obtained four times a day at 0000, 0600, 1200, and 1800 UTC, and can be freely downloaded from http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/.

A boundary layer observational campaign was conducted from 1100 Local Time (LT) 17 to 1400 LT 23 December 2016 in Baitapu Town (41.6841°N, 123.4160°E) about 8 km from the southern edge of the main urban zone of Shenyang (Fig. 1b). The Model Chuangzhi Tan Kong-1 (CZTK-1) sounding system, developed by the Institute of Atmospheric Physics of the Chinese Academy of Sciences, was used to measure the vertical distributions of WS, WD, T_a, and RH, with detective resolution of 0.1 m s^{-1}, 0.1°, 0.1°C, and 0.1%, respectively. Sounding balloons were released at an open balcony of a low building (height < 3 m) eight times per day at 0200, 0500, 0800, 1100, 1400, 1700, 2000, and 2300 LT, and a total of 50 groups of profile data were obtained. The ascending velocity of the sounding balloons was about 150 m min^{-1}, and sounding data were recorded at an interval of 1 s. The detection duration was about 20–40 min, and the detection height usually reached up to 1500–4500 m. It should be noted that no precipitation occurred from 17 to 21 December during the haze event but snow weather lasted during 22–23 December after the haze event. Following the methods used in Liu et al. (2015), vector winds at different observational heights were first calculated based on the vertical profiles of WS and WD, and then interpolated at each 50 m AGL. The profiles of T_a and RH were averaged every 10 m after data quality control, and then potential temperature (θ) was calculated.

The atmospheric boundary layer height (ABLH) can be estimated by using the vertical potential temperature profiles from sounding data based on the theory of boundary layer evolution, with the ABLH estimated at the altitude where the potential temperature first exceeds the minimum potential temperature within the boundary layer by 1.5 K (Nielsen-Gammon et al., 2008; Hu et al., 2014).

2.4 *Back trajectory analyses*

The HYSPLIT model from the NOAA was used to analyze the transport path of atmospheric pollutants during the haze event. Two-day back trajectory analyses were conducted for the four cities and the information is listed in Table 1.

3. Results and discussion

3.1 *Overview of the haze event in the central Liaoning city cluster*

3.1.1 *Identification of hazy episode*

A haze event is characterized by an apparent decrease of VIS less than 10 km and ambient RH smaller than 80% lasting for several hours (Fu et al., 2008; Leng et al., 2016). Under the conditions of 80% < RH < 90%, the event is usually regarded as a complex of haze–fog co-occurring or transition (Leng et al., 2014; 2016), while under the conditions of RH ⩾ 90%, it is referred to as a fog event.

Figure 2 depicts the temporal variations of hourly mean PM mass concentrations and some surface meteorological parameters in Shenyang, Anshan, Fushun, and Benxi from 16 to 21 December 2016. As shown in Figs. 2a–d, VIS remained below 10 km during 17–21 December in all cities except for Anshan where VIS declined to below 10 km after the midday of 18 December. RH mostly ranged from 60% to 90% in Shenyang and Fushun and from 40% to 90% in Anshan and Benxi (Figs. 2i–l). Since $PM_{2.5}$ concentration was quite high during the whole period, this event is classified as a haze event in the present study. During the observational period, air quality in most cities reached Level 5 (daily air quality index (AQI) > 200) according to the ambient air quality standards in China, which means the central Liaoning city cluster suffered from a persistent and severe haze pollution. Here, AQI is a numerical rating and can be calculated by using air pollutant concentrations over a specified averaging period.

Table 1. Information of back trajectory simulation

City	Position	Target altitude	Starting time
Shenyang	41.77°N, 123.50°E	200, 500, and 1000 m AGL	1500 LT 16 December 2016
Anshan	41.08°N, 123.00°E	200, 500, and 1000 m AGL	0300 LT 17 December 2016
Fushun	41.88°N, 123.95°E	200, 500, and 1000 m AGL	0600 LT 17 December 2016
Benxi	41.32°N, 123.78°E	200, 500, and 1000 m AGL	1200 LT 17 December 2016

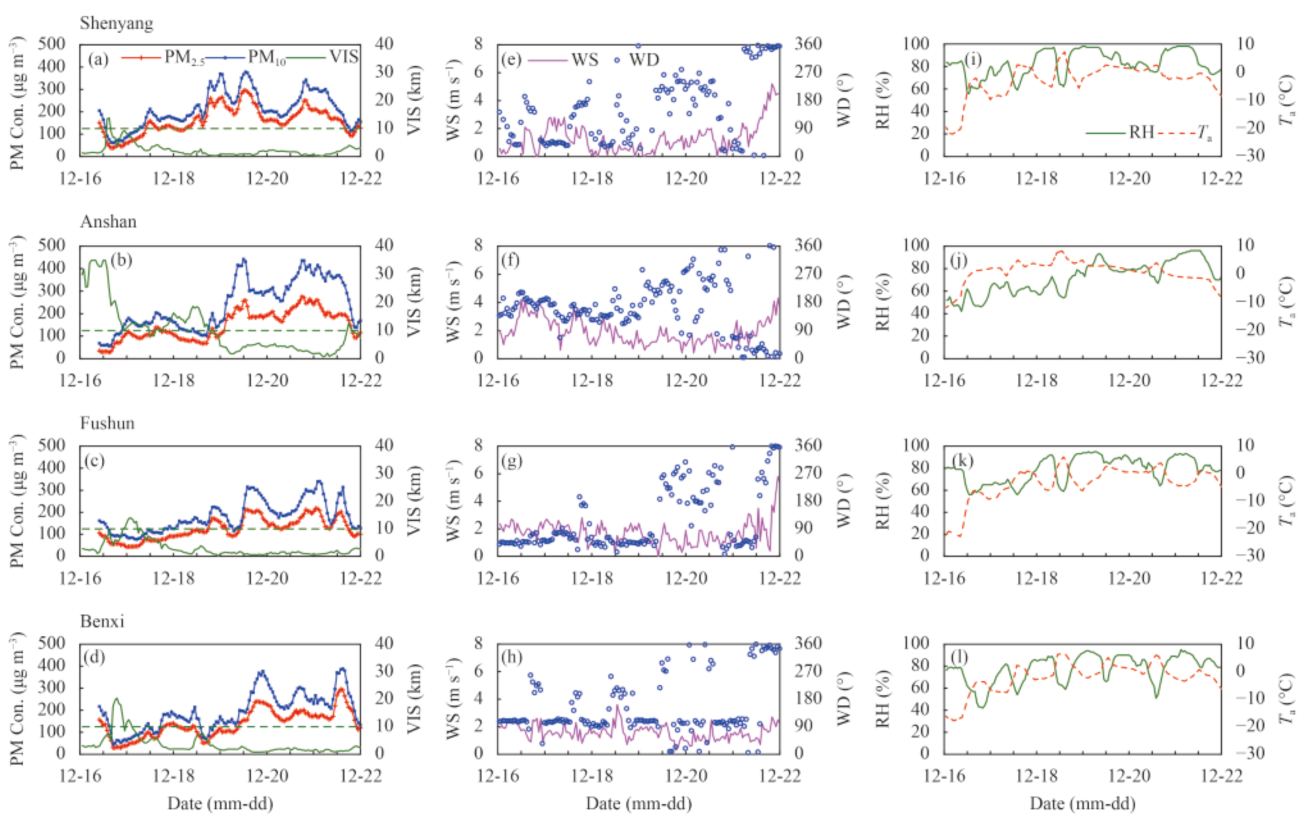

Fig. 2. Temporal variations of hourly mean (a–d) $PM_{2.5}$ and PM_{10} mass concentrations from environmental monitoring stations and atmospheric visibility, (e–h) wind speed and wind direction at 10-m height, and (i–l) relative humidity and air temperature at 2-m height from meteorological stations in Shenyang, Anshan, Fushun, and Benxi from 16 to 21 December 2016. The dashed lines in (a–d) are the visibility at 10 km.

3.1.2 *Particulate mass concentration and atmospheric visibility*

Overall, PM_{10} and $PM_{2.5}$ concentrations varied similarly during the haze event in all cities. The maximum hourly $PM_{2.5}$ in different cities ranged from 276 to 355 μg m^{-3} and the maximum hourly PM_{10} in different cities ranged from 378 to 442 μg m^{-3}. The lowest hourly VIS reached 0.14, 0.64, 0.18, and 0.63 km in Shenyang, Anshan, Fushun, and Benxi, respectively (Figs. 2a–d). Taken Shenyang as an example, the $PM_{2.5}/PM_{10}$ ratio averaged during the haze event reached 75.3% (not shown), which is consistent with results from previous literatures that low visibility is influenced remarkably by fine particles in Northeast China (Ma et al., 2011; Zhao et al., 2013a, b). During the haze event, $PM_{2.5}$ concentration was larger in Anshan (158.3 ± 22.2 μg m^{-3}) and Shenyang (157.9 ± 31.0 μg m^{-3}), and relatively smaller in Fushun (121.3 ± 48.9 μg m^{-3}) and Benxi (135.6 ± 60.8 μg m^{-3}). By comparing the variations of $PM_{2.5}$ and VIS in Fushun with those in Anshan, it is interesting to find that Anshan had larger $PM_{2.5}$ concentration but still higher visibility during 17–18 December, which was probably due to a lower RH (40%–60%) condition in Anshan. Some previous studies have indicated that an increase in RH within a certain range can cause significant VIS degradation (Stock et al., 2011; Liu et al., 2012).

3.1.3 *Surface meteorological conditions*

Wind speed at 10 m height was lower than 2 m s^{-1} for most of the hazy period but increased to higher than 4 m s^{-1} on 21 December in all cities except for Benxi (Figs. 2e–h). Wind direction in Shenyang changed frequently but was basically southeast or southwest during the haze event (Fig. 2e). In other three cities, WD also turned into southeast or southwest when PM concentrations increased rapidly on 19 December (Figs. 2f–h). T_a mostly ranging from –10 to 5°C was correlated negatively with ambient RH (Figs. 2i–l).

3.1.4 *Synoptic patterns*

The 925-hPa geopotential height (unit: m) fields at 0800 LT 18–21 December are shown in Fig. 3. The central Liaoning city cluster was located in the front of a weak and slowly moving low pressure system on 18–20 December (Figs. 3a–c). The weak pressure gradients represented by very sparse isobaric lines resulted in weak large-scale air circulation and low wind speed in the near-surface layer in this region. Such stable synoptic conditions favored the accumulation of air pollutants and inhibited their horizontal dilution. With the cold high pressure moving towards the southeast, the surface isobaric lines over this region became much denser on 21 December (Fig. 3d), and strong winds were conductive to the dispersion of air pollutants.

3.2 *Effects of boundary layer structure on the haze event*

3.2.1 *Characteristics of horizontal wind fields*

Vector wind field reflects the regional flow spatial characteristics; a larger vector wind indicates better dispersion conditions for air pollutants, and vice versa (Wu et al., 2007). Figure 4 shows the average daily 10-m wind fields over Liaoning during 16–21 December 2016.

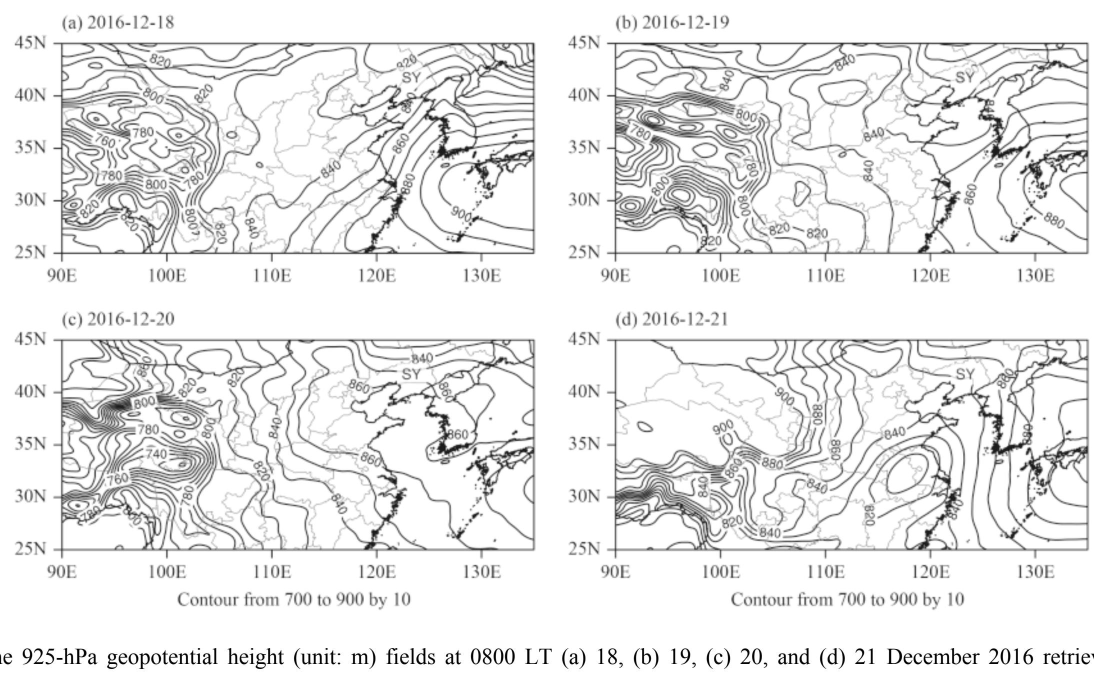

Fig. 3. The 925-hPa geopotential height (unit: m) fields at 0800 LT (a) 18, (b) 19, (c) 20, and (d) 21 December 2016 retrieved from the ECMWF reanalysis data. The "SY" denotes Shenyang.

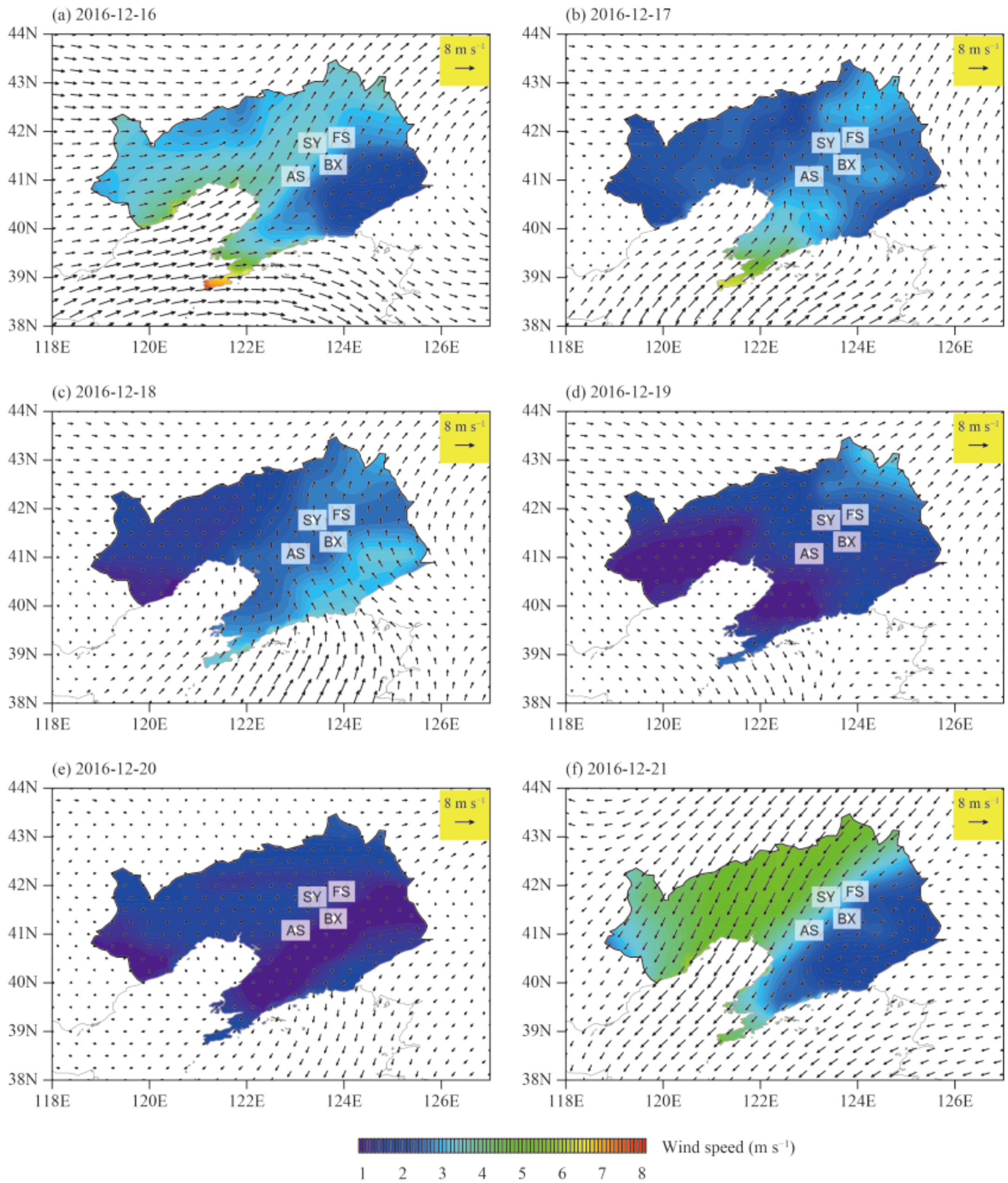

Fig. 4. Spatial variations of the daily mean wind field retrieved from the ECMWF reanalysis data over Liaoning Province from 16 to 21 December 2016. SY, FS, AS, and BX represent Shenyang, Fushun, Anshan, and Benxi, respectively.

Liaoning was dominated by the southwesterly and westerly flows on 16 December and since the following day the central Liaoning city cluster was mainly controlled by the southeasterly flow that was favorable for the transportation of water vapor from the Bohai Sea to this region and resulted in high ambient RH condition. The daily mean wind speed over the central part of Liaoning decreased day after day from 16 to 20 December, which was favorable for the accumulation of air pollutants in this region. With the arrival of cold and dry air masses brought by the strong northeasterly flows on 21 December, the heavy haze event ultimately ended.

3.2.2 *Characteristics of vertical wind distribution in Shenyang*

The vertical distribution of vector wind from 0200 LT 18 December to 0200 LT 22 December 2016, measured from the boundary layer experiment in Shenyang, is shown in Fig. 5. It can be seen that during 0200–1100 LT 18 December wind speed at all heights below 2 km decreased rapidly with time, and wind direction rotated with increasing height in a clockwise direction. Meanwhile, PM concentrations at surface began to increase

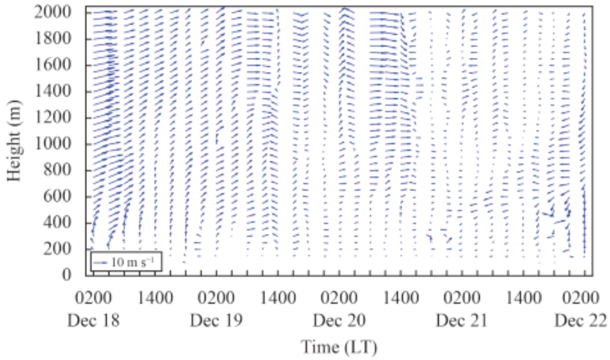

Fig. 5. Time–height cross-section of winds from the sounding data in Shenyang from 0200 LT 18 December to 0200 LT 22 December 2016.

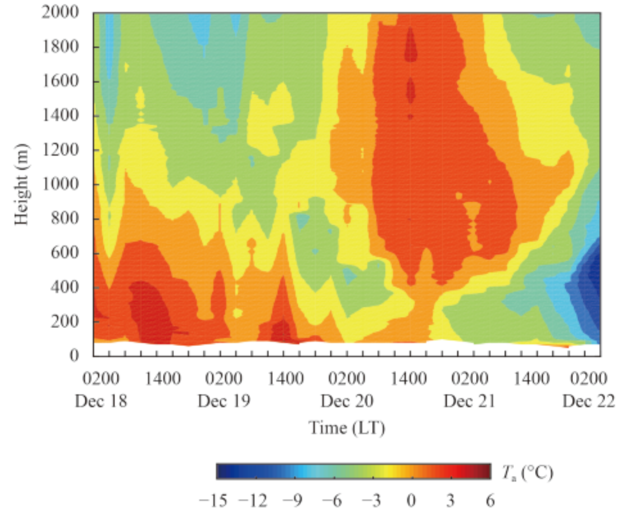

Fig. 6. Time–height cross-section of air temperature from the sounding data in Shenyang form 0200 LT 18 December to 0200 LT 22 December 2016.

sharply (Fig. 2a). Weak southerly and southwesterly flows then prevailed until 1100 LT 19 December, corresponding with $PM_{2.5}$ increasing to approximately 300 μg m^{-3} (Fig. 2a). Wind speed was still very small at low altitudes (< 600 m), whereas winds fluctuated frequently at high altitudes, contributing to the fluctuation of PM concentrations.

3.2.3 *Characteristics of vertical temperature distributions in Shenyang*

The vertical distribution of air temperature based on sounding data from 0200 LT 18 December to 0200 LT 22 December 2016 in Shenyang is shown in Fig. 6. With the increasing PM concentrations during the haze event, T_a in the boundary layer decreased obviously, and the depth of the warm advection declined until 1400 LT 20 December. These stable and upper-layer warm atmospheric conditions were very favorable for the maintenance of the haze pollution event.

To clearly outline the atmospheric stability in ABL, Fig. 7 shows potential temperature profiles in Shenyang at 0500, 1100, 1700, and 2300 LT from 18 to 22 December 2016. From 0500 LT 18 December to 0500 LT 19 December, a potential temperature inversion layer existed from the surface to the height of 1500 m, and the inversion intensity gradually increased with time. During this period, the surface $PM_{2.5}$ concentration increased from 123 to 209 μg m^{-3}. After 0500 LT 19 December, θ varied very small at the low altitudes of ABL (< 800 m),

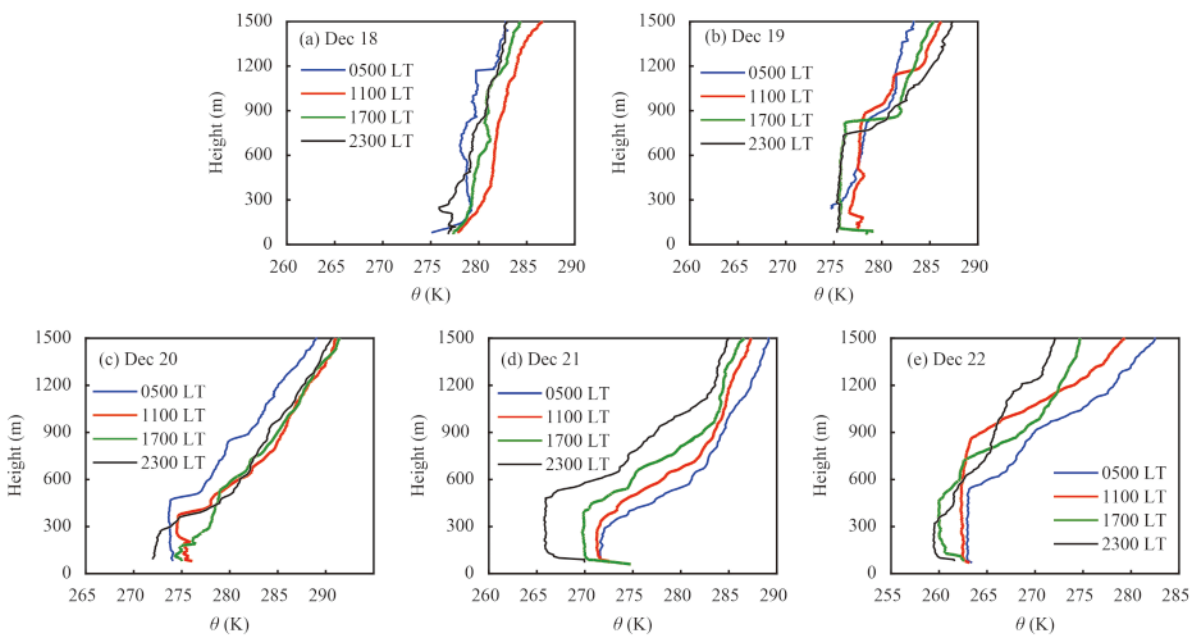

Fig. 7. Potential temperature profiles from the sounding data in Shenyang at 0200, 0800, 1400, and 2000 LT from 18 to 22 December 2016.

but the enhancement of the potential temperature inversion was apparent at high altitudes of ABL. The potential temperature inversion intensity gradually increased from 8.9 K km^{-1} at 1700 LT 19 December to 15.8 K km^{-1} at 2300 LT 20 December. Additionally, the bottom of inversion height gradually decreased from approximately 900 m at 1700 LT 19 December to approximately 300 m at 2300 LT 20 December, corresponding to a very high PM concentrations on the following day. After that, the bottom of inversion height increased to 900 m again at 1100 LT 22 December, which strengthened the vertical mixing of air pollutants and favored with the dilution of air pollutants at surface. It should be noted that the warm advection near the ground at 1700 and 2300 LT 19, 21, and 22 December was mainly due to the heat island effect over the urban region.

3.2.4 *Evolution of the ABLH in Shenyang*

The ABLH plays an important role in the evolution of haze episodes. Decreasing the height of ABL can normally hold the pollutants within the shallow surface layer, suppress the vertical atmospheric dilution, and finally lead to regional environment shrouded by pollution (Kim et al., 2007; Leng et al., 2016). The ABLH estimated by using sounding data was plotted in Fig. 8. The regular diurnal variation of the ABLH, i.e., highest in the middle of the day and lowest at nighttime, was not so typical during heavy pollution period. From 0200 LT 18 December to 1100 LT 19 December, the ABLH was mostly below 400 m, and $PM_{2.5}$ and PM_{10} concentrations during this period reached 265 and 370 μg m^{-3}. When the ABLH increased rapidly to 900 m at 1400 LT 19 December and remained larger than about 600 m until 0800 LT 20 December, $PM_{2.5}$ and PM_{10} concentrations dropped to 142 and 180 μg m^{-3}, respectively. As ABLH remained lower than 400 m from midday on 20 December to midday 21 December, the air pollution in the near-surface layer enhanced again. On the whole, the ABLH measured by ball sounding was typically below 400 m during heavy pollution episodes. Such shallow ABL led to high PM concentration in the near-surface layer.

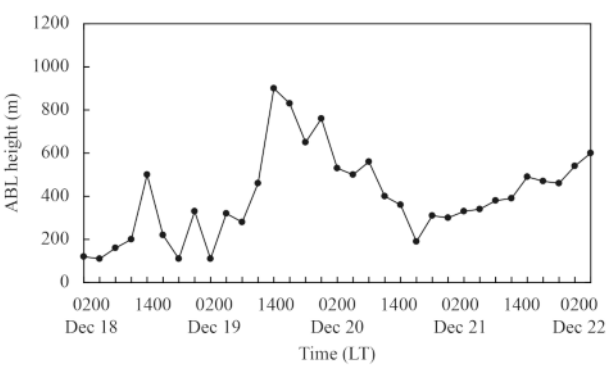

Fig. 8. Evolution of the atmospheric boundary layer height (ABLH) from the sounding data in Shenyang.

3.3 *Impacts of air mass pathways*

Different aerosol transportation paths were observed in the four cities during the haze event according to the 2-day back trajectory analyses at 200, 500, and 1000 m AGL (Fig. 9). The ending time of these back trajectory simulation is listed in Table 1, corresponding with the first peak when $PM_{2.5}$ > 200 μg m^{-3}. The air masses at 200 m AGL were generated from the Bohai Sea and passed through North Korea and southeastern Liaoning before arriving at Shenyang, Fushun, and Benxi. These air masses carried water vapor and led to high RH conditions. However, the air masses at all three altitudes in Anshan originated from western China (Fig. 9b), resulting in lower RH in Anshan than in the other three cities (Fig. 2j). The transportation paths of air masses at 1000 m AGL in Fushun and Benxi were similar to that of the air mass that arrived in Anshan. The air masses at the middle altitude of 500 m AGL in Shenyang originated from the North China Plain, where anthropogenic activities are intense and severe haze pollution is common. The transport pathways may demonstrate that in addition to the high local emissions of aerosols, the trans-boundary transport of aerosols from the North China Plain could play a role in exacerbating the air pollution.

4. Conclusions

The characteristics of the ABL structure during a persistent, severe regional haze event over the central Liaoning city cluster during 16–21 December 2016 were analyzed based largely on measurements from an ABL observational experiment and PM concentrations at the surface. The mean $PM_{2.5}$ concentration during the haze event was larger in Anshan (158.3 ± 22.2 μg m^{-3}) and Shenyang (157.9 ± 31.0 μg m^{-3}) and smaller in Fushun (121.3 ± 48.9 μg m^{-3}) and Benxi (135.6 ± 60.8 μg m^{-3}). The distribution of daily horizontal wind fields at 10 m that were retrieved from the ECMWF reanalysis data during 16–21 December were strongly related to allocation of the surface pressure field. A southerly flow in the near-surface layer prevailed over the most regions of Liaoning. Wind speed decreased rapidly after 16 December, and the superposition of a weak wind field with weak horizontal wind resulted in air stagnation, ultimately causing deterioration in air quality during the haze event. A potential temperature inversion layer existed within the entire ABL at the earlier hazy episode,

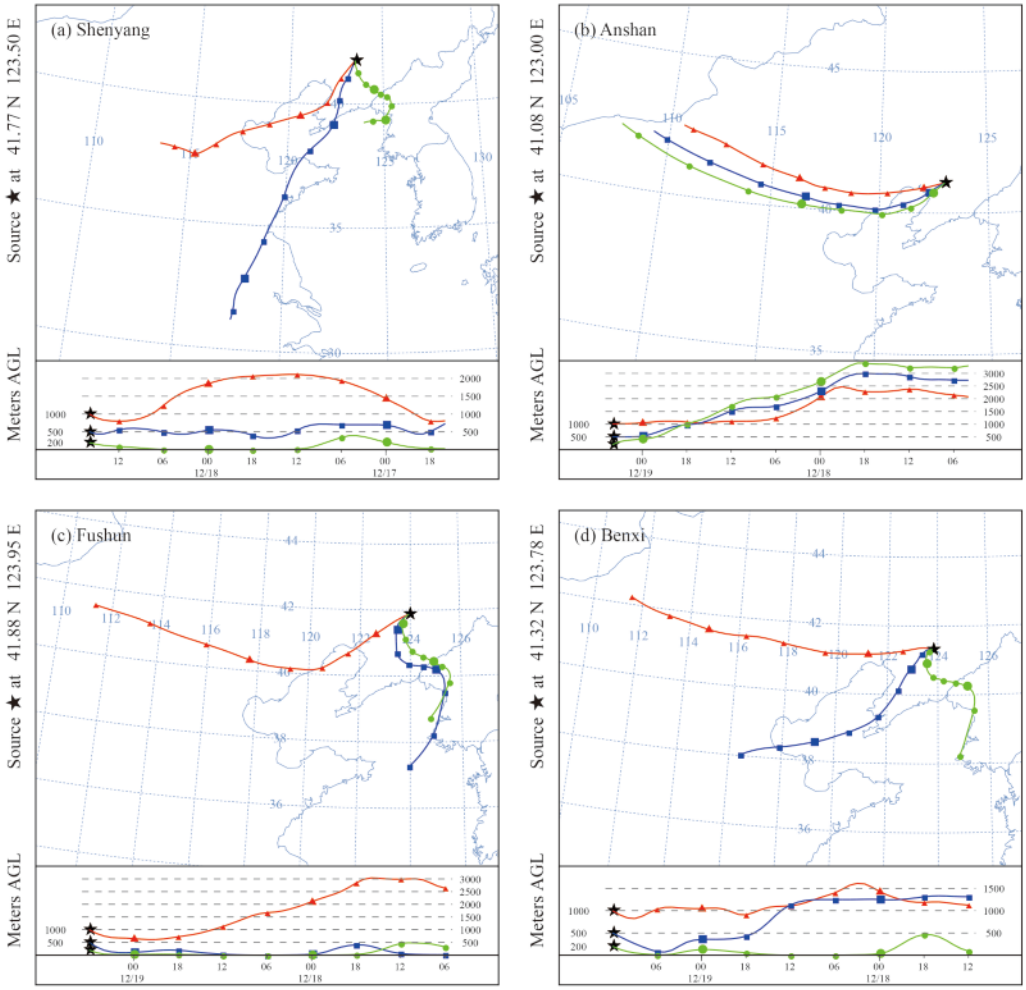

Fig. 9. The HYSPLIT 48-h backward trajectory at (a) Shenyang starting from 1500 LT 16 December 2016, (b) Anshan starting from 0300 LT 17 December 2016, (c) Fushun starting from 0600 LT 17 December 2016, and (d) Benxi starting from 1200 LT 17 December 2016.

such stable atmospheric conditions were very favorable for the formation and maintenance of the haze pollution event. After, the inversion layer enhanced apparently, with the bottom varying between 300 and 900 m, corresponding to the fluctuation of PM concentration at surface. The ABLH measured by ball sounding was typically less than 400 m during a heavy pollution episode and exhibited a negative correlation with $PM_{2.5}$. Such a low ABLH would concentrate pollutants in the near-surface layer.

The back trajectory analyses indicated that the air masses at the lower altitude of 200 m AGL in all cities originated from North Korea and passed over the Bohai Sea, except for the air masses arriving in Anshan, which caused lower humidity there compared with that in the other cities. The air masses at the higher altitudes of 500 and 1000 m AGL in Shenyang were generated from the North China Plain, where anthropogenic activities are intense and haze pollution is severe. In conclusion, the unfavorable meteorological conditions within ABL played as the external reason of this haze formation, besides the anthropogenic emissions of pollutants as the basic cause.

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