Vertical-distribution Characteristics of Atmospheric Aerosols under Different Thermodynamic Conditions in Beijing

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ABSTRACT

Understanding the vertical distribution of atmospheric aerosols is crucial to elucidating their spatial distribution and the formation of extreme air pollution events. Based on multisource data from specialized aircraft, lidar, and conventional surface observations with meteorological reanalysis, the vertical distribution of atmospheric aerosols and related changes during two air pollution cases in Beijing in the spring of 2012 were analyzed and compared. The results indicated that temperature inversion occurred in the atmospheric boundary layer in both cases. Aerosols accumulated considerably within the inversion layer, and the vertical distribution of the aerosol concentration was consistent with the relative humidity. However, the vertical distributions of the pollution layer thickness, aerosol concentration, and particle size differed significantly under different temperature-inversion conditions, primarily because of differences in the air pollution-diffusing abilities, which depended on vertical changes in the atmospheric thermodynamic structure. When radiation inversion occurred, the diurnal variation in the vertical distributions of aerosol and relative humidity was notable: The air pollution layer was thin in the morning, but the aerosol and particle size became more vertically uniform during the day, and the aerosol concentration and relative humidity near the surface decreased sharply because of enhanced pollutant vertical diffusion, which was influenced by newly developed unstable thermodynamic stratification. During the temperature inversion resulting from coupled subsidence and advection, the inversion layer was higher and more stable, allowing it to inhibit the vertical diffusion of pollutants, which subsequently caused long-lasting and thick pollution with a higher aerosol concentration and relative humidity at lower levels alongside a relatively unchanging vertical distribution of particle sizes. Moreover, in the daytime, as the southerly airflow strengthened below the inversion layer and the mixed-layer height increased, the pollution and wet layers thickened, and the aerosol concentration increased rapidly because of pollutant transport to the Beijing region.

Keywords: Aerosol; Aircraft detection; Temperature inversion; Vertical distribution.

INTRODUCTION

Urban air pollution is a serious environmental problem causing considerable harm to human health in China (Hou et al., 2012; Gao et al., 2013; Sun et al., 2013; Hou et al., 2016; Sharm et al., 2018). Air pollution is mainly caused by large volumes of pollutants with low atmospheric dispersion (Lang et al., 2017; Wang et al., 2018). Atmospheric dispersion and temperature stratification within the atmospheric boundary layer play a crucial role in pollutant dilution, specifically inversion (Quan et al., 2011; Quan et al., 2014; Li et al., 2015; Liu et al., 2015; Sun et al., 2016; Zhang et al., 2016; Cai et al., 2017). According to the formation mechanism of inversion, temperature inversion at low levels can be classified into radiation, advection, sink, turbulent, and frontal inversions. Thus far, many studies have revealed the relationship between inversion and air pollution and various weather phenomena, such as haze, fog, and precipitation (Rosenfeld, 2000; Liu et al., 2009; Liu et al., 2013; Jiang et al., 2015; Li et al., 2016).

Studies on the formation, spatiotemporal distribution, and physicochemical properties of serious air pollution in the Beijing-Tianjin-Hebei (BTH) region have made considerable progress. In particular, they have revealed that the region’s stable weather background, local pollution source intensity, special orographic conditions, and secondary aerosol and extraneous pollutant transportation are important contributors to the formation of atmospheric pollution (He et al., 2001;
Zhou et al., 2005; Duan et al., 2006; Ge et al., 2012; Zhao et al., 2013; Wang et al., 2014). During air pollution events, the typical thermodynamic environments for the formation of heavily polluted conditions in Beijing and its neighboring regions include radiation, subsidence, and advection inversions. In addition, field studies on pollutants and atmospheric boundary layer have revealed that aerosols at a high concentration are mainly distributed below the altitudes of 4500 m; the size distribution of aerosol particles varies at different levels, and aerosols clearly accumulate at the bottom of the inversion layer (Zhang et al., 2011; Lu et al., 2012; Sun et al., 2012; Tang et al., 2015; Yang et al., 2017; Zhong et al., 2017).

Elucidating the vertical distribution of pollutants is crucial to a thorough understanding of the spatial distribution of atmospheric aerosols and providing a large-scale perspective on the formation of extreme air pollution events. Various detection methods can be used to obtain the vertical-distribution characteristics of aerosols. Through satellite observation, the horizontal and vertical distribution of aerosols can be obtained over all areas, without the requirement of meteorological observation; however, the aerosol vertical structures are not described in detail using this method because of the low spatial resolution (Tian et al., 2017). Lidar has also been widely used in studies of aerosol vertical distribution to enable observation of more elaborate structures (Pace et al., 2015). For example, aerodynamic topographic removal effects have been studied on the basis of lidar measurements in Beijing (Sun et al., 2016, 2017); however, lidar observation is limited to aerosols and meteorological elements at fixed locations. Meteorological towers can help ascertain city canopy height, whereas kite-airship observations focus on meteorological elements, but their observation heights and areas are restricted. By contrast, although aircraft detection is subject to limitations related to takeoff conditions, flight duration, altitude, and cost, an aircraft platform can detect much higher and carry various meteorological and aerosol monitoring instruments to measure three-dimensional distribution (Zhang et al., 2006; Chen et al., 2009). Few studies have investigated the vertical distribution and variation characteristics of aerosols together with meteorological elements in the boundary layer of the BTH region by combining direct detection using an aircraft with surface, conventional, and special observations.

On April 14 and 17, 2012, two air pollution events in Beijing were observed using one weather-modification aircraft, and a complete dataset of aerosols and meteorological elements within the atmospheric boundary layer was collected. The spatiotemporal distribution of aerosols during these two events was significantly different. On the basis of aerosol data from an aircraft, micropulse lidar, and surface observations combined with conventional and special meteorological observation data, this paper compares the formation, diffusion, and influence of pollution on the spatiotemporal distribution of aerosols during two air pollution events in Beijing and investigates the vertical distribution and characteristics of aerosols under different thermal conditions.

OBSERVATION AND DATA

Aircraft and Airborne Instruments

A Yun-12 type precipitation-enhancement seeding aircraft belonging to the Beijing Weather Modification Office was employed to detect aerosols and other meteorological elements. The aircraft has a practical ceiling of 7000 m, a cruising speed of 290 km h$^{-1}$, a maximum flight duration of 4.4 h, and a maximum range of 1340 km. This aircraft was specially modified, installed with advanced aerosol and cloud droplet detection instruments (Droplet Measurement Technologies Inc., USA), such as a passive cavity aerosol spectrometer probe (PCASP-100X); a cloud, aerosol, and precipitation spectrometer; and a precipitation imaging probe. In addition, the aircraft was fitted with an integrated meteorological measurement system (AIMMS-20), a dewpoint meter, and a GPS-based navigation and positioning system. The PCASP-100X probe enabled measurement of atmospheric aerosols ranging from 0.1–3 µm at a sampling volume rate of 1 cm$^3$ s$^{-1}$, which was divided into 30 bins at different intervals. These instruments enabled continuous measurement of cloud, aerosol, and precipitation particle spectra; water content; and basic meteorological elements, such as temperature, pressure, humidity, and wind, as well as flight positions and attitudes.

Campaign

Aircraft detection data were collected on April 14 (Case 120414) and April 17 (Case 120417). The two flights flew under clear-sky conditions with few clouds. For Case 120414, the aircraft flew over the Beijing region and the city of Baoding (38.8°N–40.2°N, 115.4°E–116.6°E). The flight began at 9:52 a.m. and ended at 1:16 p.m. (China Standard Time). The aircraft began detecting after takeoff from Shahe Airport in Beijing’s Changping District before flying southwest until over the city of Baoding in Hebei province. The aircraft rose to a maximum height of 3645 m and then descended to 544 m. Subsequently, it flew over the 4th Ring Road of Beijing at a height of 1500 m and performed detection at 1500 and 1800 m. Finally, the aircraft flew at 1500 m and returned to Shahe Airport. This flight obtained the distribution characteristics of aerosols in different regions and levels. The flight path is illustrated in Figs. 1(a) and 1(b).

For Case 120417, the aircraft remained near Shahe Airport, where it took off and landed. The flight path was mostly located in the Changping area (116.2°E–116.39°E, 40.03°N–40.24°N). The flight began at 12:23 a.m. and ended at 3:25 p.m. (China Standard Time). The aircraft ascended to 3668 m and then descended to 3600 m. Between 3600 and 600 m it undertook a spiral-shaped detection at 300-m intervals to obtain the vertical-distribution characteristics of aerosols across all levels. Figs. 1(c) and 1(d) illustrates the complete flight path.

Data

Upper-air and conventional surface meteorological observation data and 1° × 1° NCEP/NCAR reanalysis data were used, along with special meteorological data, such as...
Fig. 1. Flight paths (red for takeoff and blue for landing) of Case 120414 and Case 120417: (a) three-dimensional flight path of Case 120414, (b) two-dimensional flight path of Case 120414, (c) three-dimensional flight path of Case 120417, and (d) two-dimensional flight path of Case 120417.

L-band second-level sounding data from the Beijing Observatory and wind profiler data from Haidian and Yanqing districts. The 1290-MHz wind profiler located at Haidian Weather Station (39.98°N, 116.28°E) is a boundary-layer radar with a maximum detection height of 3500 m. This profiler can obtain wind data at a 50-m vertical resolution at 5-min time intervals. The 445-MHz wind profiler located at Yanqing Weather Station (40.45°N, 115.97°E), which can observe up to 6270 m at 6-min time intervals, was employed to study the influence of midtroposphere wind field on pollutant vertical dispersion. Aerosol concentration was measured using a USA 1400a tapered element oscillating microbalance instrument with a 5-min resolution at the aerosol monitoring station located in Baolian Stadium Park in Haidian District (39.94°N, 116.3°E). The data quality was controlled by integrating extreme value, data continuity, and multiparameter correlation comparison with other methods (Zhang et al., 2015). The Shangdianzi Atmospheric Background Station (40.65°N, 117.01°E) is 55 km away from downtown Miyun and approximately 290 m above sea level, located on a small hillside of Shangdianzi Village in Miyun County, northeast of Beijing. The land use over this area is relatively simple and dominated by farms and fruit-tree plantations. No intense natural or large local anthropogenic emission sources are present within a 30-km radius (Yan et al., 2010; Cheng et al., 2016). Aerosols were also observed using a micropulse lidar (MPL4102) placed in an observation cabin in Baolian Stadium Park. All observation instrument sites are illustrated in Fig. 2. Fernald (1984) method is used for extinction coefficient inversion.

RESULTS AND DISCUSSION

Temporal Variation in Fine Particulate Matter Concentration and Visibility

Figs. 3(a)–3(d) displays the temporal variation in the surface fine particulate matter (PM$_{2.5}$) concentration and
Fig. 2. Distribution of conventional meteorological observation and aerosol monitoring stations (YQ: Yanqing Weather Station; BL: Baolian Stadium Park Station; GXT: Beijing Observatory; HD: Haidian Weather Station; SDZ: Shangdianzi Atmospheric Background Station; SHJC: Shahe Airport in Changping District).

Fig. 3. PM$_{2.5}$ concentration and visibility time series at Baolian Stadium Park Station and Shangdianzi Atmospheric Background Station on April 14 (a and c) and 17 (b and d) (Cases 120414 and 120417, respectively).

visibility at the urban Baolian Stadium Park Station and suburban Shangdianzi Atmospheric Background Station during Cases 120414 and 120417. Combined with the meteorological factors, the comparison indicates that changes in the PM$_{2.5}$ concentration and visibility were markedly different between the two cases; however, they both occurred under clear-sky conditions with few clouds. For Case 120414, the PM$_{2.5}$ concentration at Baolian Stadium Park Station
continued to rise from 6:00 a.m. to a maximum value of 93 µg m$^{-3}$ at 10:00 a.m., and visibility fell to 8 km with light air pollution. After 10:00 a.m., the PM$_{2.5}$ concentration decreased significantly and remained lower than 35 µg m$^{-3}$ in the afternoon, and visibility improved to greater than 15 km. The PM$_{2.5}$ concentration at Shangdianzi Atmospheric Background Station remained lower than 35 µg m$^{-3}$ with visibility greater than 15 km. In Case 120417, the PM$_{2.5}$ at Baolian Stadium Park Station exhibited a general upward trend with decreasing visibility. During this event, the PM$_{2.5}$ increased slowly from 1:00 a.m. to 8:00 a.m., and air quality worsened between 8:00 a.m. and 9:00 a.m. because of severe pollution with the PM$_{2.5}$ concentration reaching a maximum of 163 µg m$^{-3}$, followed by subsequent fluctuating increases. Visibility decreased from 20 km overnight to 6 km in the morning, which worsened to 5 km in the afternoon. The PM$_{2.5}$ concentration at the Shangdianzi Atmospheric Background Station slightly changed between 1:00 a.m. and 12:00 p.m.; however, from 1:00 p.m. to 4:00 p.m., it increased to 90 µg m$^{-3}$, and visibility decreased from 15 to 12 km.

**Vertical Distribution of Aerosols**

Observations from the micropulse lidar indicated that aerosol concentrations below 300 m were higher in the morning of Case 120414 and that in the daytime, aerosols in the lower layers spread gradually to higher levels, reaching up to 2500 m from 1:00 p.m. to 2:00 p.m. on April 14. Correspondingly, the distribution of aerosols was more uniform in the whole layer, and aerosol concentration near the surface decreased significantly (Fig. 4(a)). In Case 120417, the high-concentration aerosol layer was only below 800 m in the morning of April 17, which thickened to 1000 m during the daytime. The aerosol concentration clearly increased between 0 and 400 m in the afternoon (Fig. 4(b)).

**Aircraft Detection Results**

Aerosol detection data from an airborne PCASP probe during the aircraft’s takeoff and landing in the two flights was used to effectively reflect the distribution of vertical aerosol concentration over the Beijing region. From Fig. 5, in Case 120414 the aerosol concentration below 300 m was higher during takeoff on the morning of April 14, in the range of 4000–5000 cm$^{-3}$. Above 300 m, the aerosol concentration decreased dramatically to under 1000 cm$^{-3}$. At 1:00 p.m., when the aircraft was landing, the vertical distribution of aerosols below 1500 m was more uniform, with an average of 2000–3000 cm$^{-3}$. In Case 120417, the aerosol concentration was higher below 800 m during takeoff at midday April 17 in a range of 5000–6000 cm$^{-3}$. During the afternoon landing, the high-concentration layer of aerosols thickened to 1100 m, and aerosol concentration increased to 6000–6500 cm$^{-3}$. The structures of the vertical distribution of aerosol concentrations detected by the aircraft in both cases were consistent with that of the surface micropulse lidar observation.

Size is a crucial physical parameter for classifying aerosol particles suspended in the atmosphere. Fig. 6 illustrates the vertical distribution of aerosol median diameters in Case 120414 and Case 120417. The aerosol median diameter below 200 m was relatively small during the aircraft’s takeoff on April 14. During landing and below 2000 m, most of the particles’ median diameters ranged from 1 to 1.5 µm and appeared to have a more uniform vertical distribution.
distribution. On April 17, the vertical structures of the aerosol median diameters differed little during takeoff and landing. The aerosol particles below 1000 m were small, and their median diameters were concentrated at approximately 0.5 µm. Above 1000 m, the aerosol concentrations decreased with increasing height, while the median diameters increased.

Due to the limitation of equipment, the overall observation range of the aerosol is 100 nm to 3 µm in this study, so the particle size distribution characteristics of the aerosol number concentration under the accumulation mode (100 nm–1 µm) and the coarse mode (> 1 µm) are discussed as follows. Fig. 1 is the particle size distribution of aerosol number concentration in two different flight processes. There are 2 modes for aerosol at different heights according to the number of concentration distribution; aerosol number concentration under the accumulation mode is significantly higher than number concentration under the coarse mode. In the process of aircraft takeoff (Case 120414), the atmospheric vertical diffusion condition is poor. Under the accumulation mode, the aerosol number concentration is demarcated at 300-m height, and the aerosol number concentration decreases significantly under the accumulation mode above 300-m height. In the process of aircraft landing (Case 120414), the atmospheric vertical diffusion condition is better, and the distribution difference of aerosol number concentration is not obvious under the accumulation mode. In the aircraft takeoff and landing process (Case 120417), there is a clear demarcation for the aerosol number concentration at 1200-m height under the accumulation mode and the aerosol number concentration decreases obviously under the accumulation mode above 1200-m height (Fig. 7, left).

Aerosol volume concentration distribution can indirectly represent the distribution characteristics of mass concentration. Accumulation mode aerosols’ volume concentration was higher under takeoff stage below 300 m in Case 120414. The accumulation mode aerosols below 300 m was diluted because of diffusion to high altitude at the landing stage. The vertical structure of aerosol volume concentration distribution in the stage of takeoff and landing in in Case 120417 was very small, and the volume concentration of the accumulation mode aerosol below 1200 m was high (Fig. 7, right).
Fig. 7. Particle size characteristics of vertical distribution of aerosol number concentration (left) and mass concentration (right).
This analysis indicates that the vertical distribution and temporal changes in aerosols differed markedly between the two pollution cases; even within the same event, the changes in aerosol concentrations observed at the urban and atmospheric background stations were inconsistent. Thus, vertical atmospheric thermal or dynamic conditions likely play a critical role. Hence, additional comparative analysis was conducted to determine the cause of the aerosol spatiotemporal differences observed during the two pollution events.

**DIFFERENT THERMAL CONDITIONS AND THEIR EFFECTS ON AEROSOLS**

**Background Atmospheric Circulation**

Background atmospheric circulation is a critical factor that can determine the atmosphere’s vertical diffusion structure. Fig. 8 illustrates the upper-air and surface atmospheric circulations during the two pollution events. As aforementioned, on the day of each event the Beijing region was under clear-sky conditions with few clouds and no moving weather systems at both the upper and lower levels. In Case 120414, the Beijing region was influenced by westward airflows originating from the bottom of the Baikal Lake low vortex at 500 hPa in the upper air and controlled by a weak pressure field at the front of the convergence zone. In Case 120417, northwest airflows were prevalent over Beijing due to a high pressure ridge developing at 500 hPa in the upper air, and the surface pressure field presented a high-south and low-north pattern. Consequently, the Beijing region was located in front of the convergence zone.

**Effects of Radiation Inversion**

Fig. 9 plots the temperature inversion below 300 m over the Beijing region on the morning of April 14 along with height and relative humidity. From Fig. 10, the vertical velocity at lower levels was weak at 8:00 a.m. on April 14 with a low wind speed in the near-surface layer. Therefore, the morning temperature inversion on April 14 developed because of air cooling in the near-surface layer resulting from cloudless and calm wind conditions during the night that caused radiation inversion. The stable boundary layer was below 300 m and inhibited the diffusion of air pollutants; consequently, the aerosol concentration increased more over urban areas. However, at the Shangdianzi Atmospheric...
Background Station 290 m above sea level, the wind speed was relatively higher, and the conditions for the formation of a radiation temperature inversion were unfavorable. Thus, the air quality at this station was excellent.

From Fig. 9, the temperature inversion at 300 m remained present at aircraft takeoff at 9:52 a.m. Because of the presence of direct sunlight, the surface temperature increased by 6°C compared with that at 8:00 a.m. The atmosphere below 300 m exhibited an unstable stratification, and the humidity was relatively higher, with an aerosol concentration just high enough to be detected by the aircraft and lidar. The calculated correlation coefficient between the aerosol concentration and relative humidity below 2000 m was 0.949, which passed a significance level test of 0.001. The wind-profile detection at 10:30 a.m., illustrated in Fig. 10(b), revealed that the southerly winds below 500 m in the boundary layer enhanced to 4 m s⁻¹, with the surface PM$_{2.5}$ concentration decreasing significantly. Following further warming in the boundary layer, during landing after 1:00 p.m. the temperature vertical-decline rate exceeded the dry adiabatic lapse rate below 1000 m over Shahe Airport, and the atmospheric instability further strengthened. Fig. 10(a) reveals a clear air-ascending movement below 500 hPa in the Beijing region, a result of low-level aerosols diffusing into the upper level. The aerosol concentration and aerosol median diameters in the vertical direction appeared to be well distributed; by contrast, the aerosol concentration and humidity in the near-surface layer decreased evidently.

**Fig. 9.** Vertical profiles of temperature (left) and relative humidity (right) from L-band second-level radiosonde observation (blue) over Beijing at 8:00 AM on April 14 and during takeoff (yellow) and landing (red) on April 14 (Case 120414).

**Fig. 10.** Time changes in (a) vertical pressure velocity and (b) Haidian wind profiler observation over Beijing on April 14 (Case 120414).

**Mixed Effects from Advection and Subsidence Inversions**

Fig. 11 illustrates the vertical profiles of temperature, humidity, and wind for the 8:00 a.m. sounding and during takeoff and landing in Case 120417. For the 8:00 a.m. sounding on April 17, clear multilayer temperature inversions were present, and the temperature-inversion layers were high up, scattered mainly between 400–600 m and 1000–1300 m. Below 800 m, the humidity level was high, and
aerosol concentration was also higher in the morning. Combined with the data from Figs. 12 and 13, the dynamic structures over Beijing demonstrated low-level convergence ascending and upper-level divergence sinking on April 17. The warm advection and water vapor convergence from the southwest super low-level jet (Fig. 11(c)) below 1000 m in the morning resulted in the formation of temperature inversion between 400 and 600 m and a wet layer below 800 m. Figs. 12(a) and 12(b) reveal warm advection above 1000 m with a vertical sinking motion. Under the combined effects of warm advection and subsidence warming, a stronger temperature-inversion layer formed between 1000 and 1300 m.

In Case 120417, the near-surface temperature warmed rapidly on the morning of April 17, and the temperature inversion between 400 and 600 m disappeared at noon during aircraft takeoff (Fig. 11(a)). The mixed-layer height increased, and vertical diffusion enhanced, but the temperature-inversion layer between 1000 and 1300 m remained stable because of the strong mixed effects of warm advection and subsidence warming. This further inhibited the upward spread of air pollutants and water vapor, which led to the pollution layer thickening in the morning. From 2:00 p.m. to 4:00 p.m., the low-level southwesterly wind noticeably strengthened (Fig. 13). The layer then thickened until its height extended to 1400 m, much higher than the 1000 m observed at 8:00 a.m. (Fig. 12(b)). The height of the mixed layer increased further (Fig. 11(a)) with a thickening wet layer (Fig. 11(b)) in favor of strong convergence ascending. However, the strong temperature-inversion layer near 1300 m remained, and the air pollution layer slightly thickened during landing in the afternoon. The vertical distribution of the aerosol particle sizes also remained largely the same. In comparison, the vertical distributions of aerosol concentration and relative humidity demonstrated agreement, and their correlation coefficients were 0.93 and 0.95 during takeoff and landing, respectively, both passing the significance level test of 0.001.

The mixed-layer height at the bottom of the temperature-inversion layer in the afternoon was significantly increased compared with that at 8:00 a.m. on the morning of April 17. The vertical diffusion of the air pollutants grew in the afternoon; however, the aerosol concentration at lower levels substantially increased (Fig. 4(b)). This indicated that outside pollutants were transported to Beijing from the southwest, and the range of the air pollution expanded to the northern mountainous regions. Accordingly, the surface PM$_{2.5}$ concentration at the Shangdianzi Atmospheric Background Station significantly increased in the afternoon.
CONCLUSIONS

An inverse temperature structure appeared within the atmospheric boundary layer during air pollution events, and aerosols accumulated below these inversion layers. The vertical distribution of the aerosol concentration was consistent with that of the relative humidity. By contrast, the air pollution layer thickness, aerosol concentration, and particle size vertical distribution varied significantly under different temperature-inversion conditions. This finding is attributable to the air pollution diffusion, which is affected by vertical changes in the atmospheric thermodynamic structure.

Under radiation inversion conditions, the diurnal variation in the vertical distribution of aerosols according to the relative humidity was evident. In the morning, a relatively thin and low air pollution layer was present with high humidity near the surface. During the daytime, as thermal conditions improved, the temperature inversion was destroyed, and the stratification became unstable. The vertical diffusion abilities of the pollutants then increased, and air pollutants correspondingly dispersed upward. The vertical distributions of the aerosol concentrations and particle sizes became uniform, and the aerosol concentration and relative humidity in the near-surface layer decreased significantly.

Due to the influence of subsidence and advection inversions, the air pollution layer was thick and persistent. This condition was primarily a result of higher temperatures in the inversion layer and stability resulting from the subsidence warming the mid-high-level air and warm advection. The effects of a stably maintained temperature inversion that sank limited aerosol diffusion in the vertical direction, which further concentrated pollutants, resulting in increased humidity and little change to the vertical distribution of particle sizes at lower levels.
With stable atmospheric circulation, in the daytime, when the southerly airflow below the mixed-inversion layer strengthened and the mixed-layer height lifted, the air pollution layer and wet layer thickened, and outside pollutants were transported to the Beijing region on a southerly wind. The aerosol concentration considerably increased at the lower levels, and the air pollution range expanded to the northern mountainous regions.

ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China (2016YFA0602004, 2017YFC1501405, 2016YFC0202000: Task 3), the Ministry of Science and Technology of the People’s Republic of China (IUMKY201724), and the National Natural Science Foundation of China (41475109, 41775129).

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Received for review, April 11, 2018
Revised, July 16, 2018
Accepted, August 26, 2018