Vertical Profiles of Aerosol Composition over Beijing, China: Analysis of In Situ Aircraft Measurements

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ABSTRACT

Aerosol samples were collected over Beijing, China, during several flights in November 2011. Aerosol composition of nonrefractory submicron particles (NR-PM₁) was measured by an Aerodyne compact time-of-flight aerosol mass spectrometer (C-ToF-AMS). This measurement on the aircraft provided vertical distribution of aerosol species over Beijing, including sulfate (SO₄), nitrate (NO₃), ammonium (NH₄), chloride (Cl), and organic aerosols [OA; hydrocarbon-like OA (HOA) and oxygenated OA (OOA)]. The observations showed that aerosol compositions varied drastically with altitude, especially near the top of the planetary boundary layer (PBL). On average, organics (34%) and nitrate (32%) were dominant components in the PBL, followed by ammonium (15%), sulfate (14%), and chloride (4%); in the free troposphere (FT), sulfate (34%) and organics (28%) were dominant components, followed by ammonium (20%), nitrate (19%), and chloride (1%). The dominant OA species was primarily HOA in the PBL but changed to OOA in the FT. For sulfate, nitrate, and ammonium, the sulfate mass fraction increased from the PBL to the FT, nitrate mass fraction decreased, and ammonium remained relatively constant. Analysis of the sulfate-to-nitrate molar ratio ($[\text{NO}_3^-]/[\text{SO}_4^{2-}]$) further indicated that this ratio was usually less than one in the FT but larger than one in the PBL. Further analysis revealed that the vertical aerosol composition profiles were influenced by complex processes, including PBL structure, regional transportation, emission variation, and the aging process of aerosols and gaseous precursors during vertical diffusion.

1. Introduction

Atmospheric aerosols are important components of the Earth system, playing significant roles in global climate change, regional visibility, and public health

(Fenger 1999; Pope and Dockery 2006). Aerosols, especially fine particles, change the energy balance of the climate system by altering Earth's radiative equilibrium directly and indirectly (Twomey 1977; Noone et al. 2000; Dockery 2001; Schwartz et al. 2002; Tian et al. 2018). Furthermore, aerosols and their precursors from megacities and large urban areas have significantly influenced

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atmospheric chemistry and radiative forcing on regional to global scales (Madronich 2006; Lawrence et al. 2007). Currently, the large uncertainties surrounding the impacts of aerosols are major barriers to accurate prediction of future anthropogenic-induced climate change (IPCC 2007). Knowledge on the vertical distribution and chemical composition of aerosols is required not only to estimate the global budget and the impact of aerosols on climate but also to provide key insight into the aerosol evolution process (Osborne and Haywood 2005; Heald et al. 2011).

Beijing, China, is located at the northwest border of the North China Plain, surrounded by mountains 1500–2000 m high in the north and west. Along with the rapid pace of urbanization and economic growth, the air quality in Beijing has suffered severe deterioration, with particulate matter (PM) being one of the top pollutants (Duan et al. 2004; Quan et al. 2013, 2017; Liu et al. 2018). Atmospheric pollutants have been intensively studied based on ground measurements in Beijing (Liu et al. 2012; Xin et al. 2010, 2014; Sun et al. 2010; Huang et al. 2010; Sun et al. 2013; Quan et al. 2014; Hu et al. 2016, 2017; Xu et al. 2018; Zhang et al. 2018); however, studies of the vertical and spatial variations of air pollutants based on aircraft-based measurements are still rare. To understand the vertical distribution and chemical evolution of submicron aerosols over Beijing region, aircraft measurements with an aerosol mass spectrometer (AMS) were performed. In this paper, we present the vertical distributions of aerosols chemical compositions to understand the influences of different sources and evolution processes.

2. Experimental measurements

a. Flight information, instruments, and weather background

An instrumented Yun-12 aircraft was used to conduct vertical measurements of aerosols and meteorological variables (Zhang et al. 2009; Chen et al. 2013; Quan et al. 2017). The true airspeed of the aircraft was about 200 km h⁻¹; individual flights lasted about 4 h. A relatively fixed flight pattern was used with quasi-circular horizontal legs over the inner Beijing city, as shown in Fig. 1. After takeoff from the Shahe Airport, the aircraft climbed and flew over the Beijing inner city and spiraled down around the rectangle of the fourth ring from 2100 to 600 m with a vertical interval of 300 m. During each flight, the airplane conducted approximately three to six horizontal rectangular legs of about 70-km circumference, and it took about 30 min to complete every leg. After finishing this quasi-circular flight pattern over the inner city, the aircraft spiraled down to the Shahe

Airport and then conducted measurements of vertical profiles up to about 3600 m above ground before landing. The diameter was about 10 km in these profiling flights, and it took about 30 min. The Shahe Airport is not for commercial use, and there are only a few flights per day. The effect of aircraft emissions is therefore very small, and the perturbation to measured vertical distributions of aerosols due to aircraft emissions should be insignificant.

Key aircraft measurements included chemical composition of aerosol, temperature, humidity, winds, and 3D aircraft position. Aerosol chemical composition was measured with an Aerodyne compact time-of-flight aerosol mass spectrometer (C-ToF-AMS). Compared with traditional methods for aerosol chemical composition measurements (e.g., filter-based techniques), the Aerodyne AMS has demonstrated the capability to measure aerosol composition on aircraft platforms with high time resolution (Bahreini et al. 2003; Schneider et al. 2006; Morgan et al. 2009; DeCarlo et al. 2008; Bahreini et al. 2009; Dunlea et al. 2009; Liu et al. 2017; Schroder et al. 2018). The meteorological variables, which included temperature, relative humidity, barometric pressure, and wind, were measured with Aircraft Integrated Meteorological Measurement System (AIMMS)-20 (Advantech Research, Inc.). The sample air was introduced into the aircraft cabin through the isokinetic aerosol sampling inlet (model 1200, Brechtel Manufacturing, Inc.) and split to the AMS using dedicated stainless steel flow splitters (Hermann et al. 2001). Details of the AMS were presented in previous publications (Jimenez et al. 2003; DeCarlo et al. 2006; Drewnick et al. 2005). In addition, the height-dependent ambient pressure has significant effects on sample flow rate, particle transmission in aerodynamic lens, and flight velocity in size chamber. To avoid these errors caused by varied ambient pressure, a pressure controller was mounted upstream of the inlet of the AMS and maintained a fixed pressure during flight (Bahreini et al. 2008). To keep the flow rate constant, the fixed pressure should be lower than the pressure at maximum flight height. In this work, the pressure controller was set to 500 hPa, and the calibration was also performed under this pressure.

There was a total of three flights in November 2011. On 10 November, a high pressure system was located to the east of Beijing (Fig. 2a), which favored the development of local atmospheric circulations. Under this weather condition, there was generally weak wind in the Beijing region. The wind profile also indicated that the wind was very weak under 700 hPa (Figs. 3a,b). On 11 November, the Beijing region was at the south edge of a low pressure system (Fig. 2b). Under this weather

FIG. 1. Illustration of the typical flight pattern (11 Nov 2011) during the aircraft campaign. The pentacle and triangle represent locations of the center of Beijing city and Shahe Airport, respectively. The white lines represent the second to fifth rings surrounding the central Beijing and the central Chang'an street of Beijing city (straight line).

condition, the wind under 850 hPa was still very weak, while the wind between 850 and 700 hPa changed to northwest (Figs. 3c,d). On 16 November, the Beijing region was at the south edge of a high pressure system (Fig. 2c). Under this weather condition, the Beijing region was under control of southwest wind under 700 hPa (Figs. 3e,f). The weather conditions during the flights were clear, cloudy, and cloudy on 10, 11, and 16 November, respectively (Fig. 4).

b. Data analysis

Standard ToF-AMS data analysis software packages (SQUIRREL, version 1.50) were used to deconvolve mass spectrum and obtain mass concentrations of chemical components. Mass concentrations derived from the AMS are reported as micrograms per standard cubic meter ($T = 273.15 \text{ K}$; $p = 1013.25 \text{ hPa}$; $\mu\text{g sm}^{-3}$), with the time resolution of 2 min. The AMS collection efficiency (CE), which accounts for the incomplete detection of aerosol species due to particle bounce at the vaporizer and/or the partial transmission of particles by the lens (Canagaratna et al. 2007), is significantly modulated by particle phase (Matthew et al. 2008). In this

study, we used a CE correction following the principle developed by Middlebrook et al. (2012). Ionization efficiency (IE) calibrations were performed regularly by using size-selected (300 nm) pure ammonium nitrate particles before and after each flight during the flying periods.

A positive matrix factorization (PMF) analysis of the organic mass spectral dataset separated organic aerosol (OA) into hydrocarbon-like organic aerosol (HOA) and oxygenated organic aerosol (OOA), corresponding to primary OA (POA) and secondary OA (SOA), respectively (Zhang et al. 2011). The application of PMF to AMS OA spectra has been described in detail previously (Ulbrich et al. 2009; Lanz et al. 2007). Briefly, PMF is a bilinear unmixing model that identifies factors that serve to approximately reconstruct the measured organic mass spectra for each point in time; each factor is composed of a constant mass spectrum and a time series of mass concentration, and all values in the factors are constrained to be positive (Zhang et al. 2011; Paatero and Tapper 1994). The model is solved by minimizing the sum of the weighed squared residuals of the fit (known as Q). This work followed the procedures

FIG. 2. The weather systems at 0800 Beijing standard time (BST) (a) 10, (b) 11, and (c) 16 Nov. The pentagon represents location of Beijing city. The letters G and D represent high pressure and low pressure, respectively.

identified by [Ulbrich et al. \(2009\)](#) in order to apply the PMF technique to AMS data.

3. Results and discussions

a. Vertical distribution of nonrefractory small particulate matter

The AMS detection limit was determined by filtered particle-free ambient air and defined as 3 times the standard deviations of the corresponding signals ([Zhang et al. 2005](#); [DeCarlo et al. 2006](#); [Sun et al. 2009](#)). The detection limit (for 2-min sampling period) was $0.05 \mu\text{g sm}^{-3}$ for total aerosol. In our observation, the average aerosol concentration measured by the AMS was $14.9 \mu\text{g sm}^{-3}$, ranging from 0.002 to $160.2 \mu\text{g sm}^{-3}$. Only 4% of samples had concentrations lower than $0.05 \mu\text{g sm}^{-3}$. As stated in [section 2a](#), the aircraft only went to 600 m over Beijing. The observations below this level came from the

spiral over Shahe Airport. To understand how representative the low levels over Shahe Airport were in comparison to the low levels over Beijing, the comparisons of aerosol concentration and their composition between Shahe Airport and Beijing were conducted ([Fig. 5](#)). The observations in Beijing city were conducted at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS; [Liu et al. 2012](#)). The comparisons showed that both the aerosols' mass concentration and their composition over Shahe Airport were consistent with Beijing city during the experimental period.

[Figure 6](#) showed the vertical profiles of nonrefractory small particulate matter (NR-PM₁) mass concentration and chemical species during the three flights. The NR-PM₁ mass concentrations usually remained at a fixed value at the low layer and then decreased significantly with altitude. The NR-PM₁ mass concentrations ranged

FIG. 3. Profiles of temperature (red line), dewpoint temperature (blue line), and wind over Beijing Guanyangtia meteorological station (39.8°N, 116.47°E) at (a),(c),(e) 0800 and (b),(d),(f) 2000 BST (a),(b)10, (c),(d) 11, and (e),(f) 16 Nov 2011.

from 47 to $155 \mu\text{g sm}^{-3}$ at the 0–1-km layer and from 1.7 to $14.2 \mu\text{g sm}^{-3}$ at the 3–4-km layer. Compared with mass concentration, the chemical species profiles were more complicated. There were vertical variations not only during individual flights but also among different flights. For example, the dominant components were organics (35%) and nitrate (34%) at the 0–1-km layer and changed to sulfate (47%) and ammonium (28%) at the 3–4-km layer on 11 November, while on 16 November, the dominant components at the 3–4-km layer

further changed to organics (42%) and sulfate (43%). On average, organics (35%) and nitrate (31%) were dominant components in the 0–1-km layer, followed by ammonium (15%), sulfate (13%), and chloride (5%), while in the 3–4-km layer, sulfate (44%) and organics (26%) were dominant components, followed by ammonium (22%), nitrate (7.5%), and chloride (0.5%). The aerosol composition and its concentration in the atmosphere might be influenced by several factors, including pollutant emissions, atmospheric advection/diffusion, conversion of

FIG. 4. Daily total radiation (black line) and scattered radiation (red line) during flight periods. The weather conditions were clear, cloudy, and cloudy on 10 (flight 1), 11 (flight 2), and 16 Nov (flight 3), respectively.

gaseous precursors, and aging processes (Zhang et al. 2015; Quan et al. 2015; Sun et al. 2013). As discussed below, a comprehensive data analysis was conducted to investigate the predominant factors and/or processes that influence vertical aerosol mass and composition over Beijing.

b. Role of PBL on aerosol mass concentration

Inside the planetary boundary layer (PBL), aerosols are vertically mixed by small eddy turbulences. There generally is a barrier (very low mixing rate) at the top of the PBL to prevent aerosol particles crossing from the PBL to the free troposphere (FT; Zhang et al. 2009; Quan et al. 2013). In this work, the PBL height is determined at the altitude where there is an inversion or an abrupt large change in the dewpoint temperature (Wilczak et al. 1996; Quan et al. 2013; 2017), which is calculated from the aircraft measurements of temperature and relative humidity. As Fig. 7 showed, the dewpoint had a small gradient at the lower level and then exhibited a negative gradient at a certain altitude. Based on the method introduced above, the PBL height during the three flights were defined as 1.9, 0.9, and 2.1 km on 10, 11, and 16 November, respectively (Fig. 7). The NR-PM₁ mass concentrations remained at relatively fixed values (11 and 16 November) or decreased slightly (10 November) inside the PBL, while there was usually a sharp decrease of aerosol mass concentration between

the PBL and the FT. The magnitude of the barrier at the top of the PBL can be quantitatively described by the bulk Richardson number (Ri), which is used as a measure of expected air turbulence and vertical mixing (Launiainen 1995; Sharan et al. 2003; Zhang et al. 2009), and is expressed by the follow equation:

$$R_i = (g/T_m)(\Delta T L)/(\Delta U^2 + \Delta V^2), \quad (1)$$

where g is the acceleration due to gravity (m s^{-2}); L is the vertical distance between two vertical levels (m); T_m is the mean temperature in the vertical distance L ; ΔT , ΔU , and ΔV are the differences in temperature and horizontal wind speeds (x and directions) between two vertical levels (with the vertical distance of L ; 50 m in this work). A lower Richardson number indicates a higher degree of turbulence and vertical mixing, while a higher number suggests a lower degree of turbulence and vertical mixing. The Ri was 0.09 on 10 November (Fig. 7a), the lowest among the three flights, suggesting that there was not a strong barrier to prevent aerosol particles being transported from the PBL to the FT. This result was consistent with lowest NR-PM₁ mass gradient between the PBL and the FT on 10 November among the three flights.

c. Difference of aerosol composition in PBL and FT

Similar to mass concentration, aerosol chemical compositions also showed drastic variation around the

FIG. 5. Comparison of (a) aerosol mass concentration and their composition at (c),(e) Beijing and (b),(d) Shahe Airport.

PBL top (Fig. 8). Inside the PBL or FT, the aerosol chemical composition was relatively stable; however, there was a significant variation between the PBL and FT. On average, organics (34%) and nitrate (32%) were dominant components in the PBL, followed by ammonium (15%), sulfate (14%), and chloride (4%), while in the FT, sulfate (34%) and organics (28%) were dominant components, followed by ammonium (20%), nitrate (19%), and chloride (1%). The profiles of individual components provide more detailed information. Sulfate belongs to secondary aerosols from the conversion of gaseous SO_2 through photochemical

and/or heterogeneous reactions. Its mass fraction increased significantly from the PBL to FT during all three flights (Fig. 8a). The average mass fractions of sulfate in the PBL were 10%, 13%, and 22% and increased to 18%, 44%, and 40% in the FT on 10, 11, and 16 November, respectively. For organics, it includes both primary organics (e.g., HOA) and secondary organics (e.g., OOA). Thus, its vertical variation was more complex (Fig. 8c). On 11 November, the organics fraction in FT was lower than in the PBL, while its fraction in the FT was higher than in the PBL on 16 November. Further analysis indicated that the

FIG. 6. Aerosol composition profiles on (a) 10, (b) 11, and (c) 16 Nov, including mass concentrations (black lines) and their mass fractions (pie charts).

OOA-to-HOA ratio increased significantly in the FT even though both OOA and HOA mass concentration decreased with altitude. Inside the PBL, the HOA concentration was nearly equal to or higher than OOA. In contrast, the HOA was lower than OOA by an order of magnitude in FT (Fig. 9).

Pollutants from ground emissions are mixed in the PBL by eddy turbulences within several hours, but it takes more time, usually one to several days, to pass across the PBL layer because of the low mixing rate at the top of the PBL. Besides, the pollutants in the FT may also originate from regional transportation. Hence, the lifetime of pollutants in the FT is much longer than in the PBL, which facilitates the conversion of gaseous precursors to aerosols and resulted in the opposite trends of primary aerosols (e.g., HOA) and secondary aerosols (e.g., sulfate and OOA) in the PBL and FT.

It is worth noting that nitrate is also a secondary aerosol, but its mass fraction in FT was lower than in the PBL (Fig. 8d). Such variation was contrary to the vertical trend of sulfate. To understand this inconsistency, the relationships between sulfate, nitrate, and ammonia are analyzed since the formations of sulfate and nitrate are connected by the participation of bases [mainly ammonia (NH_3)] and their precursors are likely to compete for ammonia. As shown in Fig. 10, the equivalent ratios of ammonium to the sum of sulfate plus nitrate were equal to or higher than one in both PBL and FT, indicating that ammonia was enough to neutralize the acidic sulfate and nitrate aerosols over Beijing. In other

words, the aerosols were ammonium rich in both the PBL and FT. The nitrate-to-sulfate molar ratio ($[\text{NO}_3^-]/[\text{SO}_4^{2-}]$) as a function of the ammonium-to-sulfate molar ratio ($[\text{NH}_4^+]/[\text{SO}_4^{2-}]$) was further investigated to understand sulfate–nitrate–ammonium relations (Fig. 11). Several points are noteworthy from this figure. First, the ammonium-to-sulfate molar ratio was higher than two in both PBL and FT, further supporting the ammonium-rich condition since ammonium rich can be defined as $[\text{NH}_4^+]/[\text{SO}_4^{2-}] = 1.5$ (Pathak et al. 2004). Second, a comparison of the nitrate-to-sulfate relation revealed striking differences between the PBL and FT. In general, the relative abundance of nitrate increased as the ammonium-to-sulfate molar ratio increased in ammonium-rich condition (Fig. 11), which is similar to previous studies (Pathak et al. 2004, 2009). However, $[\text{NO}_3^-]/[\text{SO}_4^{2-}]$ was usually less than one in the FT but larger than one in the PBL, further supporting the above conclusion that there was less nitrate in the FT than in the PBL.

Note, the decreasing nitrate-to-sulfate ratio from the PBL to FT was observed during other aircraft measurements (Kline et al. 2004; DeCarlo et al. 2008; Dunlea et al. 2009) and at high-elevation mountain sites around the world (Shrestha et al. 1997; Preunkert et al. 2002; Fröhlich et al. 2015). One possible explanation is that the faster production of nitrate in the PBL via gas phase ($\text{OH} + \text{NO}_2$) or particle phase ($\text{N}_2\text{O}_5 + \text{particle water}$) compared to the production of SO_2 to sulfate (Fröhlich et al. 2015). Therefore, NO_x is rapidly depleted with increasing age of air masses such that most nitrate

FIG. 7. Profiles of (left to right) temperature T , relative humidity (RH), dewpoint temperature T_d , and PM_{10} mass concentration observed by AMS, together with the calculated Ri at the top of the PBL height during flights.

formation occurs within the PBL, whereas nitrate formation within the FT is of minor importance. Further, the evaporation upon dilution with regional air with low HNO_3 and NH_3 in the FT favors the repartitioning of nitrate to nitric acid, HNO_3 preferentially goes to the gas phase, leading to the lower mass concentrations in the particle phase (DeCarlo et al. 2008). Besides, environmental T and RH can also influence the gas-particle partitioning process of nitrate (Hennigan et al. 2008; Guo

et al. 2016, 2017). More detailed research is needed to understand this phenomenon in the future.

d. Regional transport and emission variations

The mean mass fraction of aerosol components and their relative dispersion ε in the PBL and FT during the three flights are shown in Fig. 12. The value of ε is calculated as the ratio of standard deviation to the mean mass fraction of aerosol components; a higher ε

FIG. 8. Aerosol components' mass fraction profiles during flights, including (a) sulfate, (b) chloride, (c) organics, (d) nitrate, and (e) ammonium. The dashed lines represent the PBL heights on 10, 11, and 16 Nov.

indicates a bigger variation of aerosol composition. As shown in Fig. 12, ε of aerosol components in the FT was higher than in the PBL, indicating that aerosol compositions had larger variation in the FT than PBL during the three flights. For example, ε of OOA, HOA, nitrate, sulfate, ammonium, and chloride were 0.4, 1.1, 0.6, 0.4, 0.3, and 1.4 in the FT during the three flights but decreased to 0.2, 0.1, 0.2, 0.4, 0.0, and 0.6 in the PBL, respectively. The weather background analysis in section 2a shows that the FT air mass came from different direction during the three flights. The larger aerosol composition variation in FT, combined with different kinds of air masses, suggested that the aerosols in the FT were significantly influenced by regional transportation since the pollutant emissions in Beijing were different with the surrounding area because of different energy structure (Cao et al. 2011). In Beijing, oil and gas are the dominant energy resources,

leading to high emission of NO_x and low emission of SO_2 , while in the surrounding area, including Hebei, Shandong, Shanxi, and Neimeng provinces, coal is the dominant energy resource, leading to high emission of SO_2 (Zhao et al. 2012; Cao et al. 2011).

On 10 November, air mass was transported at a low speed, representing a relatively stagnant meteorological condition (Fig. 3a). In this case, the aerosols came mainly from local emission and gas-aerosol transformation, and nitrate and organics were dominant components in the FT. The mass fraction of nitrate and organics were 37% and 36%, while the fraction of sulfate was only 8%, similar with aerosols in the PBL. On 11 November, the wind in the high layer changed direction to west (Fig. 3c), but the air mass in the low layer was still from the local direction. In this case, sulfate and ammonium were dominant components in the FT rather than organics and nitrate in the PBL. On 16 November,

FIG. 9. Profiles of HOA and OOA on 10, 11, and 16 Nov: (a) their mass concentration and (b) their ratio.

the air mass was from the south (Fig. 3e). In this case, the mass fraction of OOA and sulfate in FT increased significantly. The above analysis indicated that regional aerosol transport not only enhanced the concentration of aerosols over Beijing but also affected the aerosol composition profiles.

It is noteworthy that the mass fraction of sulfate and chloride in the PBL on 16 November were higher than on 10 and 11 November, whereas nitrate in the PBL on 16 November was lower. Such a great variation might be caused dominantly by heating emissions since the heating started on 15 November. The increased coal

FIG. 10. Sum of the sulfate and nitrate equivalent concentration as a function of ammonium concentration during the flights within the PBL (red) and the FT (green).

FIG. 11. Nitrate-to-sulfate molar ratio as a function of ammonium-to-sulfate molar ratio within the PBL (red) and the FT (green).

combustion emits more chloride and SO_2 , and the latter will convert to sulfate in the atmosphere, resulting in a significant increase of sulfate and chloride during the heating period.

4. Summary

The vertical aerosol composition over Beijing, China, was measured by AMS on aircraft during November 2011. This paper analyzes the measurements. The results are highlighted as follows:

- 1) Aerosol composition varied drastically with altitude. On average, organics (35%) and nitrate (31%) were dominant components in the 0–1-km layer, followed by ammonium (15%), sulfate (13%), and chloride (5%), while in the 3–4-km layer, sulfate (45%) and organics (27%) were dominant components, followed by ammonium (22%), nitrate (8%), and chloride (0.5%).
- 2) The barrier at the top of the PBL prevented aerosol particles from crossing between the PBL and the FT, resulting in large variation of aerosol compositions around the PBL top. For organics, OOA and HOA had the same order of magnitude inside the PBL. In contrast, the OOA was higher than HOA by an order of magnitude in the FT. For sulfate–nitrate–ammonium, the ratio $[\text{NO}_3^-]/[\text{SO}_4^{2-}]$ was usually less than one in FT but larger than one in PBL.

FIG. 12. Aerosol components' mass fraction and their relative dispersion ϵ in (a) the PBL and (b) the FT during flights and (c) their difference between PBL and FT.

- 3) The regional transportation could also affect the vertical aerosol composition over Beijing because of different pollution emissions in Beijing and surrounding areas. Under the control of a west wind, the mass fraction of sulfate in the FT increased significantly; under the control of a south wind, the mass fraction of sulfate and organics in the FT increased significantly.

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