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Vertical profiles of aerodynamic size distribution for airborne particles over Yangtze River Delta*

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Based on the aircraft observations in the summer of 2003, we have studied the aerodynamic size distributions of airborne particles at altitudes ranging from 400 m to 2800 m over the central and southern areas of Jiangsu province located in Yangtse River Delta of China. The sizes of airborne particles are measured to be in a range of 0.47–30 μm with 57 channels, and their number concentrations, surface area concentrations and mass concentrations are also measured. The results show that the concentrations of airborne particles are very low above an altitude of 2000 m and the size distributions present a specific multi-peak mode by using insufficient samples. Below 1000 m, however, the concentrations of particles increase obviously, and their size distribution is similar to that at the ground level. The study also indicates that the concentrations, size distributions and median diameters of airborne particles above and below the boundary layer are very different, displaying different pollution features. Meanwhile, the results also show that the pollution level of airborne particles has a descending tendency with altitude increasing.

Keywords: airborne particles, aerodynamic size distribution, aircraft observation, Yangtse River Delta
PACC: 8670, 8670G, 8270R, 9260M

1. Introduction

Environmental pollution has become a topic that draws much attention, owing to its negative effects on human health and life quality. Atmospheric pollution, an important part of environmental pollution, has become a matter of the utmost concern globally, due to its high fluidity and complex changeability.

Airborne particles are an important air pollutant, and their pollution characteristics are determined by the different compositions and size distributions, especially particles near the ground, which may affect human health. Inhalable airborne particles can be directly inhaled into deep respiratory pathways and cause damage to health.[1−3] The properties for particles to absorb and reflect sun radiation are dependent on their diameters. Particles in the stratosphere can give rise to cold effects at ground level while particles in the troposphere can cause temperature to increase in the layer where particles absorb sun radiation.[4] Particles with diameters between 0.5 and 2.5 μm can influence visibility and landscape by reflecting light.[5,6] Particles also act as transporters in atmospheric circulation, i.e. they carry certain substances from one place to another. Particles could expedite the absorption of sulfur dioxide (SO_2) on their surfaces and the conversion into sulfate radical anion (SO_4^{2-}) and later cause acid deposition.[7−9] Particles have important effects on the formation of acid rain and as their diameters decrease, calcium ion (Ca^{2+}) concentration drops and concentrations of SO_4^{2-} and ammonium ion (NH_4^+) increase, causing the fall of pH value.[10] Therefore, scientists have done extensive research on pollution characteristics and pollution conditions of particles at the ground level.

However, one knows little about the pollution characteristics and pollution conditions from airborne particles. Airborne particles can influence radiation capability; their spatial distribution and size distribution can affect regional and global climate

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changes.[11,12] Research on the spatial distributions, size distributions and pollution characteristics of airborne particles further enable us to judge the contributions of local and regional pollution sources to air pollution and to have an understanding of the mechanism responsible for the long-range trans-boundary transport of atmospheric particles.[13−16]

Yangtse River Delta is the most prosperous area in China, and possesses developed industry with a powerful base. In order to obtain the information about size distributions and vertical distributions of airborne particles over the Yangtse River Delta in China, we carry out the aircraft observations on size distributions of airborne particles over the central and southern areas of Jiangsu Province on September 13, 2003. We study the aerodynamic size distributions of airborne particles at different altitudes to evaluate the pollution characteristics and pollution conditions with vertical distributions.

2. Sampling region and equipment

2.1. Sampling region

Model Yun-5B single propeller cargo plane, which is made in China, is used for the aircraft measurement. It flies between Changzhou and Jintan in Jiangsu Province, centred at Houyu town (E119°47', N31°44') with a radius of 15km (Fig.1). The total flight time is around 5 hours, and flight altitude is from the ground to 3000 m (7 altitudes with 2800, 2400, 2000, 1600, 1200, 800 and 400 m). The airspeed is 180 km/h.

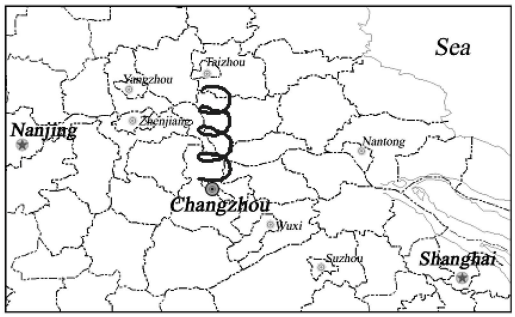


Fig.1. Flight route.

Changzhou is situated in China's most prosperous Yangtze River delta, located at 31°09'–32°04' in the north latitude, and 119°08'–120°12' in the east longitude. Changzhou has a subtropical marine and monsoon climate with four distinct seasons, annually, an average temperature of 15.5 °C, a frostless season of 227 days, a sunshine time of 2066.8 hours, a rainfall period of 124 days, a precipitation of 1066 millimetres, an evaporation amount of 1537 mm and a humidity of 77%. The whole city covers 4,375 km^2 and has a population of 3.49 million, of which the urban area covers 1,864 km^2 with 2.17 million inhabitants.

2.2. Equipment

2.2.1. Isokinetic sampling inlet

In order to avoid the flight effect on sampling airborne particles, it is necessary to use an isokinetic inlet according to the flight speed and sampling flow rate, of which the principle is the flight speed at the opening of the sampling inlet remains the same as that of the air passing by the inlet. If the sampling flow speed is smaller than the flight speed, more particles with larger diameter are sampled; on the contrary, if the sampling flow speed is higher than the flight speed, less particles with larger diameters are sampled. The isokinetic inlet is cone-shaped, with an inlet diameter of 1.5mm and a speed of 50m/s. Meanwhile, the inlet is located at 20 cm above the propeller circle to avoid the impact of turbulence on particle sampling. The sampling system and the loss of particles can be seen from Ref.[17].

2.2.2. Aerodynamic particle sizer

Model APS-3310A Aerodynamic Particle Sizer (TSI Corporation, USA，1994) is used to investigate the particle size distribution, and it has 57 channels to analyse particles with diameters of $0.43 - 30$ μm and gives results of number concentration distribution, surface concentration distribution and mass concentration distribution.

TSI APS3310A uses a mass flow meter rather than volumetric flow meter. Therefore, the measurement of flow rate is sensitive to the pressure change. Based on its design, the volumetric flow is 5 L/min of which 1 L/min is contributed to an inner nozzle and 4 L/min to an outer nozzle, in order to ensure the constant air speed of the air jet in which the particle speed is measured accurately. When it is used in the case of large change of pressure, we have to appropriately adjust the mass flow rate to a volumetric flow rate. Based on the ideal gas law equation (PV/T is constant), the mass flow rates needed at different altitudes are listed in Table 1.

Table 1. Total mass flow rates and sheath mass flow rates for APS-3310A at different typical altitudes.

altitude/m	total mass flow rate/(L/min)	sheath mass flow rate/(L/min)
2800	3.76	3.01
2400	3.96	3.17
2000	4.17	3.33
1600	4.37	3.50
1200	4.58	3.66
800	4.78	3.83
400	4.99	3.99

3. Results and discussion

3.1. Particle size distributions at different altitudes

Figures 2 and 3 indicate the size distributions of airborne particles obtained, respectively at 2800 m and 400 m altitudes during the flight over Changzhou on September 13, 2003. Figure 4 shows the size distribution at seven different altitudes. The isoline maps of number concentrations, surface area concentrations and mass concentrations are shown in Fig.5.

As the figures show, the size distributions of airborne particles vary with altitudes in some rules. As altitude increases, the particle concentration drops sharply. The number concentrations and surface area concentrations at 2800 m are three orders of magnitude lower than at 400 m, while mass concentrations are two orders of magnitude lower. All size distributions above 1600 m appear to be multi-peak distributions. The higher the altitude, the more peaks occur. Yet the size distributions below 1200 m are similar to those obtained at ground level, and the multi-peak shape disappears.[18,19]

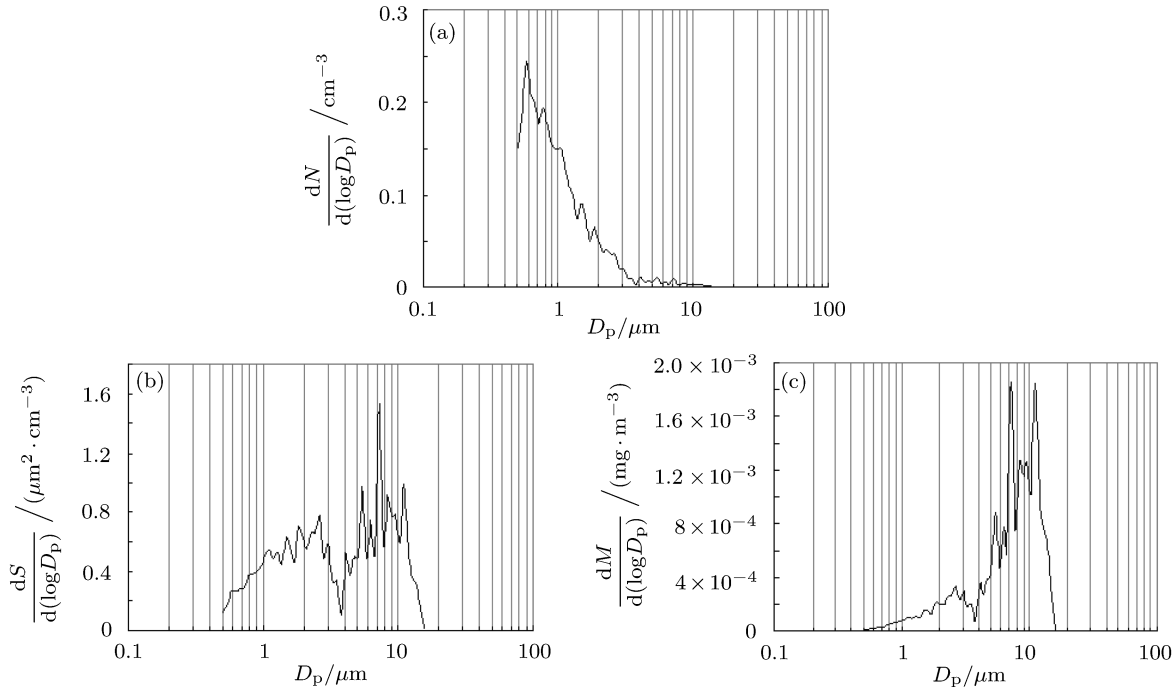


Fig.2. Size distributions of airborne particles at 2800 m (D_p denotes the diameter of particle).

The figures about number size distributions show that fine particles dominate over the airborne particles in number, and peak diameters vary a little with altitude. Above 1600 m, the peak diameters are in a range of 0.6–0.7 μm, and below 1200 m, they are between 0.5 and 0.6 μm. These situations are different

from surface area size distributions. In the size distributions at altitudes over 1600 m, large particles are predominant with peaks at around 2–4 μm in diameter; at altitudes lower than 1200 m, fine particles start to dominate while the contribution of large particles is still prominent. As altitude decreases the contribution of fine particles becomes more and more important. Large particles dominate over the mass distributions all the time, with main peaks at around 10−12 μm in diameter. As altitude decreases, the contribution of fine particles increases, with small peaks at around 0.6–0.7 μm in diameter.

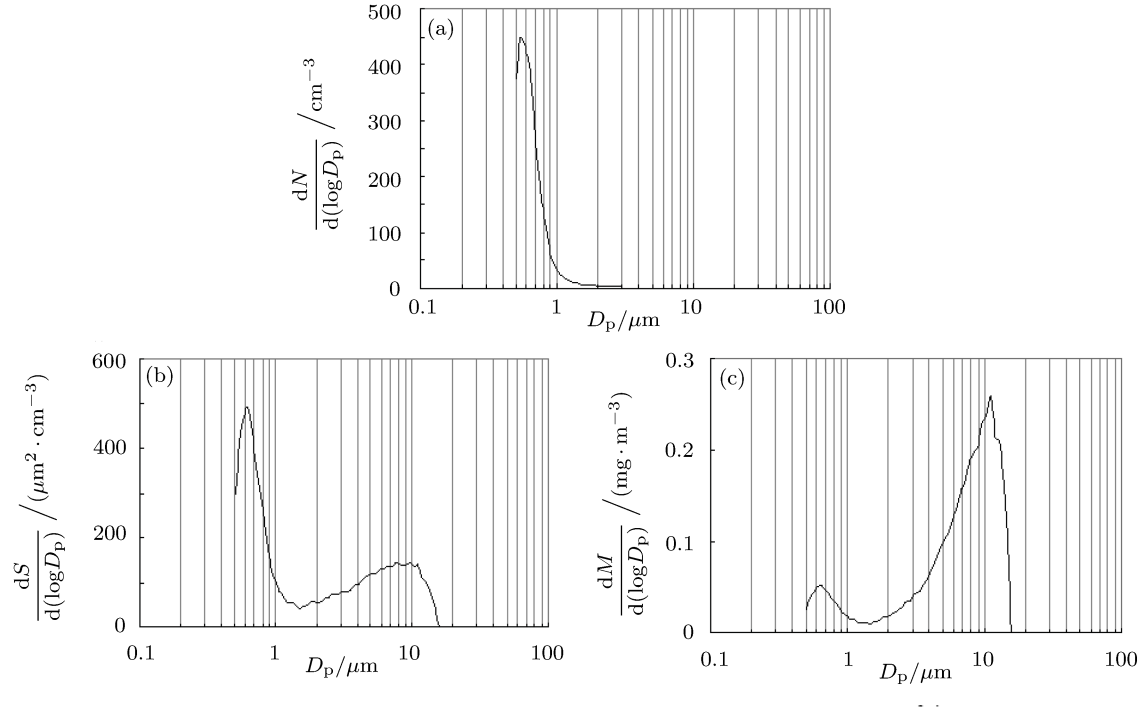


Fig.3. Size distributions of airborne particles at 400 m (D_p denotes the diameter of particle).

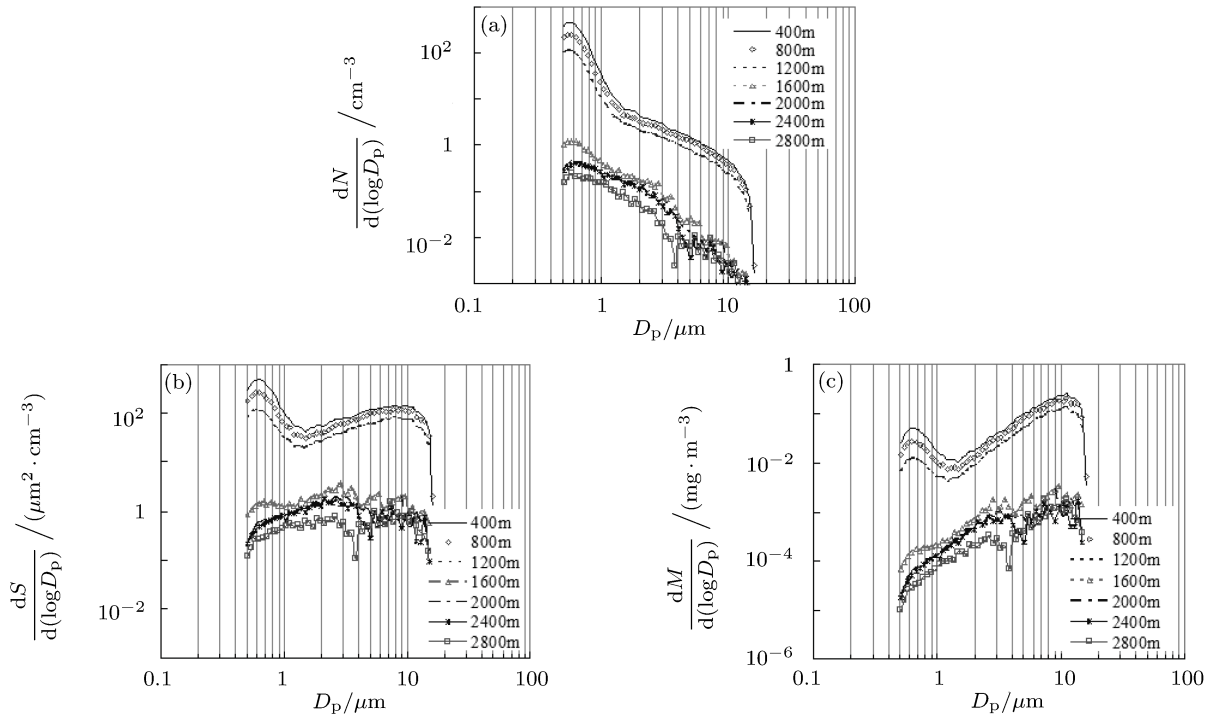


Fig.4. Size distributions of airborne particles at different altitudes (D_p denotes the diameter of particle).

As Fig.5 shows, peak diameters of number concentrations, surface area concentrations and mass concentrations are around 0.7 μm, 0.7 μm and 7–8 μm, respectively, indicating that fine particles less than 1μm in diameter dominate over number concentrations and surface area concentrations, while large particles dominate over the mass concentrations. The number concentrations, surface area concentrations and mass concentrations above 1600 m vary little, indicating the uniform distribution of particle concentrations. The concentrations of airborne particles at about 1200 m vary distinctly, and as altitude decreases, the concentration below 1200 m increases and enters into the high value area, indicating the considerable influence of ground emissions on airborne particles at low altitudes.

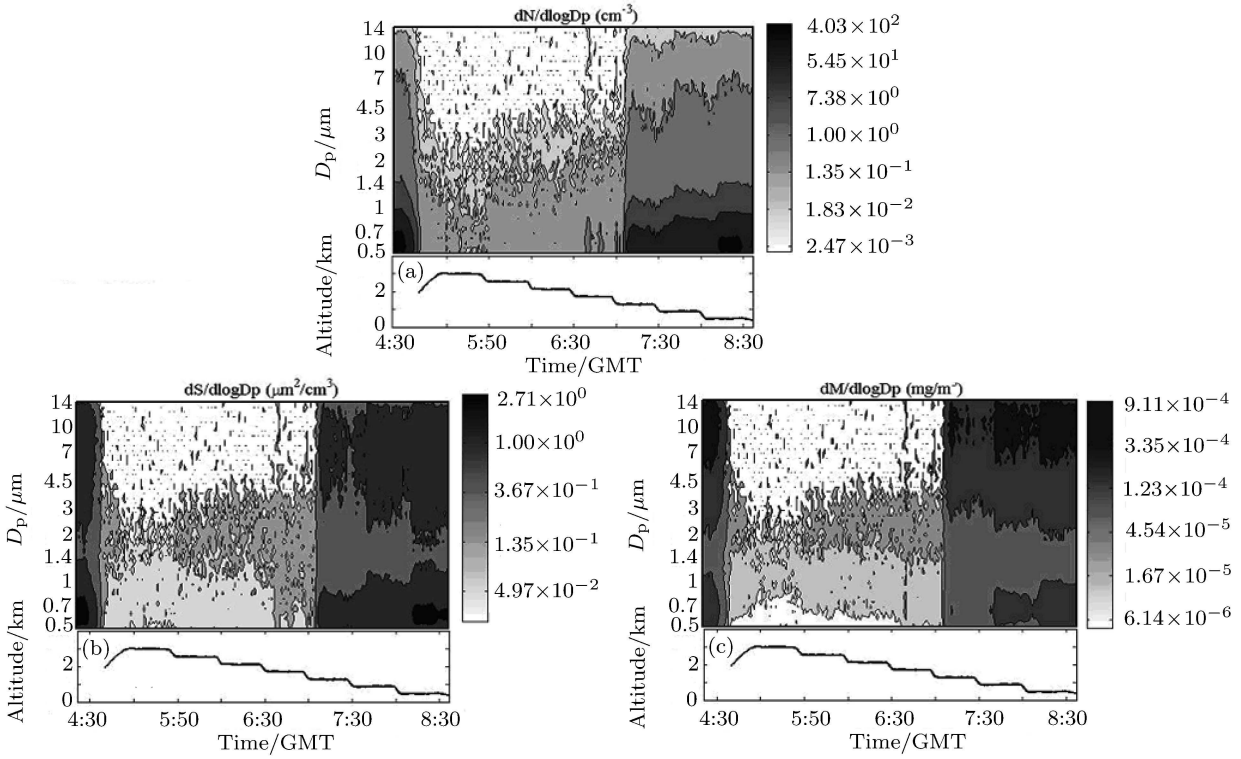


Fig.5. Isoline maps of particle number concentrations, surface area concentrations and mass concentrations at different altitudes (D_p denotes the diameter of particle).

Size distributions and their characteristics at different altitudes demonstrate that the pollution characteristics of airborne particles above 2000 m and below 1200 m are different from each other greatly. Below 1200 m, the pollution is within the mixing layer, thus particles at the ground level could be raised up and mixed within the layer and have an influence on the pollution situation and characteristics. Therefore, the results below 1200 m are similar to those of ground level particles, appearing as single-peak number concentration distributions, and two-peak surface area concentration distributions and mass concentration distributions. The height of the boundary layer is normally less than 2000 m, and the size distributions above 2000 m appear to be of discrete multi-peaks, which are quite different from those at lower altitudes. Because the concentrations of airborne particles above 2000 m are far lower than those at lower altitudes, sampling matter in the same interval is very small in quantity, which brings about a large variety of concentrations and results in the discrete multi-peaks appearing in size distributions. Even if their values each are averaged over 20–30 measured values, the concentrations of airborne particles still have a difference of 2–3 orders of magnitude among themselves. If the measurement interval is increased by 1–2 orders of magnitude, the curves of size distributions will become smooth.

3.2. Particle concentrations and median diameters at different altitudes

We summarize the number concentration, surface area concentration and mass concentration at each al-

titude and calculate their median diameters to analyse their variations with altitude. Figures 6 to 8 show that the sums of number concentrations, surface area concentrations, mass concentrations and their median diameters at different altitudes.

From the figures we can see that there are obvious inflections at 1600 m on the curves of number concentrations, surface area concentrations and mass concentrations. Particle concentrations above 1600 m are very low, but all concentrations below 1200 m increase rapidly as altitude decreases. The concentrations below 1200 m are 2–3 orders of magnitude higher than those above 1600 m.

As Figs.6–8 show, the median diameters of particles are about 0.6−0.9 μm for the number concentrations, 1–4 μm for the surface area concentrations, and 5–8 μm for the mass concentrations. The median diameters of number concentrations change significantly at 2000 m and 1200 m. The median diameters of particles above 2000 m are bigger than those below 1200 m, revealing that small particles are predominant at less than 1200 m and come from pollutants emitted from the ground and their conversions. The median diameters are relatively stable above 2000 m and below 1200 m, showing the relatively homogeneous mixing of airborne particles in both spaces.

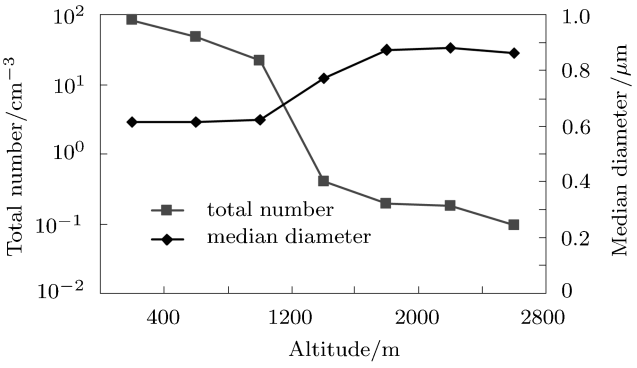


Fig.6. The sum of number concentrations and median diameters at different altitudes.

The median diameters of surface area concentrations show some complicated variations. There are two inflections at 2400 m and 1200 m. At altitudes less than 1200 m, the contribution of small particles to the surface area concentration increases rapidly as altitude decreases. At above 2400 m, the contribution of large particles turns prominent. At altitudes between 1200 m and 2400 m, the contribution of large particles increases as altitude decreases.

At above 2400 m, the contribution of small particles to mass concentrations increases as altitude decreases. When the altitude reaches 1200 m, the contribution of large particles increases sharply. As altitude continues to decrease, the median diameter stays almost unchanged, showing that large particles dominate over the mass concentrations.

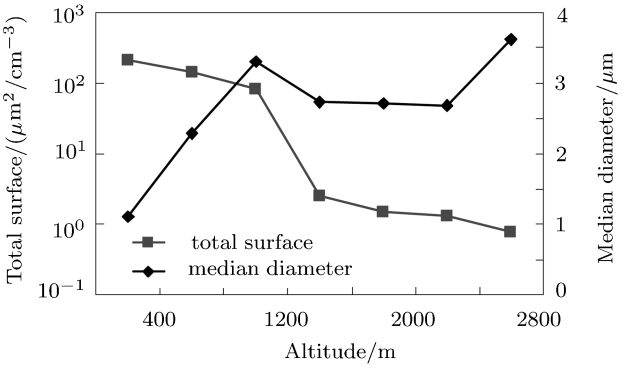


Fig.7. The sum of surface area concentrations and median diameters at different altitudes.

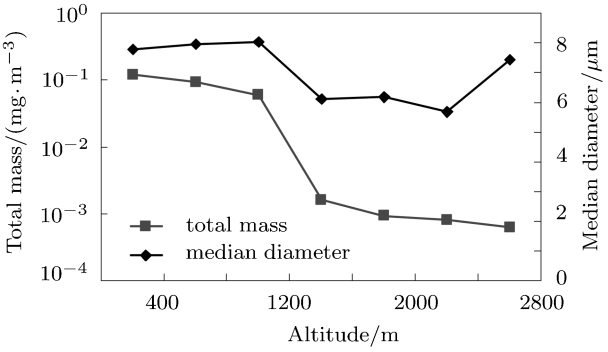


Fig.8. The sum of mass concentrations and median diameters at different altitudes.

Compared with the results at the ground level, the mass concentrations of airborne particles above 1600 m are lower. The mass concentrations below 1200 m are very high, close to medium pollution level at the ground. It is considered that high mass concentrations of particles can be found in the relevant ground area. It reflects well heavy pollution of particles in Yangtse River Delta, and pollution area is restricted not only to urban areas, but also to all regional areas. Compared with the results of gases measured in this flight, the concentrations of particles and SO_2 each have an obvious inflection between 1200 m and 1600 m (the average concentration of SO_2 is 4.54 ppb at 1200 m and 0.72 ppb at 1600 m), indicating that the boundary layer lies between 1200 m and 1600 m.

4. Conclusions

On the basis of the aircraft observations of the aerodynamic size distributions over the Yangtse River Delta, we understand the size distribution characteristics at different altitudes, especially below and above the boundary layer (mixing layer). The study indicates that fine particles less than 1μm in diameter dominate over the number concentrations and surface area concentrations, while large particles dominate over the mass concentrations of airborne particles. The concentrations of airborne particles below the boundary layer show the obvious descent with the increase of altitude, while the size distributions show unanimous characteristics, similar to those at ground level. Although the concentrations above the boundary layer show obvious gradients, the size distributions are very different from those below the boundary layer and appear to be specific multi-peak distributions, resulting from the fact that the concentrations above the boundary layer are very low and sampling matter in the same interval is very small in quantity. To obtain exact size distributions of airborne particles at high altitudes, sampling time should be extended, which should be embodied in the future aircraft observations.

The results of concentrations and median diameters show there exist an obvious gap at 1600 m for all concentrations. The concentrations above 2000 m and below 1200 m have a considerable distinction between themselves. The mass concentrations below 1200 m are very high, and can reach a medium pollution level at the ground, reflecting heavy pollution of particles in Yangtse River Delta. Median diameters are somewhat different, due to the difference of particle sources and their influence. The contribution of small particles below 1 μm in diameter to number concentration is predominant, but the particles with above 5 μm in diameter dominate over the concentration of large particles.

Aircraft observation is an effective way to study the size distributions of airborne particles at different altitudes. It should be noted that mass flow rate of TSI APS3310A needs adjusting to a steady volumetric flow rate at a high altitude, for the equipment is provided with a mass flow meter rather than volumetric flow meter. Since the aerodynamic diameter of a particle is measured by measuring the speed of a particle in jet flow, volumetric flow should be kept steady to ensure the constant air speed of the air jet. Meanwhile, the aircraft is flying at a certain high speed, so isokinetic sampling with an appropriate inlet should be designed according to the flight speed and sampling flow rate. In this experiment, we have used cone-shaped isokinetic sampling inlets. The particle concentrations drops at high altitudes significantly. Therefore, in order to accurately acquire the information about particle size distributions, the sampling time should be extended to some extent so as to obtain enough number of particles.

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