



## Chemical Mass Balance Source Apportionment of Size-Fractionated Particulate Matter in Nanjing, China

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### ABSTRACT

In recent years, atmospheric particulate matter has become the primary air pollutant in Nanjing, China. In order to support a scientific basis for particles reduction, it is of great importance to investigate the contribution of different sources to particulate matter. In this paper, the characteristics of chemical composition of observational data for size-fractionated particulate matter at Gulou site and Pukou site in Nanjing from May 2010 to April 2011 were analyzed. Emission samples of particulate matter were collected and size-fractionated particulate chemical compositions were analyzed to obtain the source profiles. A chemical mass balance (CMB) model was applied to apportion the contribution rate of different sources. Investigations show that the annual average concentrations of PM<sub>10</sub> (particles with an aerodynamic diameter of 10 μm or less) at Gulou and Pukou are  $135.8 \pm 66.4 \mu\text{g m}^{-3}$  and  $132.2 \pm 73.0 \mu\text{g m}^{-3}$ , respectively. For PM<sub>2.1</sub>, the concentrations are  $55.1 \pm 36.3 \mu\text{g m}^{-3}$  and  $64.8 \pm 40.2 \mu\text{g m}^{-3}$ , respectively. The dominant chemical constituents are SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, Ca, NH<sub>4</sub><sup>+</sup>, Cl<sup>-</sup>, Fe, Al, and K, accounting for 93.02% and 91.56% of all of the measured compositions in PM<sub>10</sub> at Gulou and Pukou. These components account for 95.23% and 93.48% of PM<sub>2.1</sub> at Gulou and Pukou. Seven types of sources, including coal combustion dust, construction dust, smelting dust, soil dust, vehicle exhaust, secondary aerosols and sea salt, are considered. The results of source apportionment show that in coarse particles, construction dust contributes a maximum of 58.9% at Gulou and 47.3% at Pukou. Smelting dust, as the second most important source, contributes 14.1% and 19.7% at these two sites. For fine particulate matter, secondary inorganic aerosols and coal dust contribution are the two largest sources accounting for 58.8% and 15.9% at Gulou and 44.2% and 39.5% at Pukou. The findings will be useful for the local government to create efficient control strategies to reduce the emission of construction dust and to pay great attention to the prevention of secondary aerosols and coal combustion dust.

**Keywords:** Size-fractionated particulate matter; PM<sub>2.1</sub>; CMB model; Emission source profiles; Source apportionment.

### INTRODUCTION

In the last decade, particulate matter (PM) has become a primary atmospheric pollutant in Nanjing, China. Atmospheric aerosols, especially fine particles (PM<sub>2.5</sub>, i.e., particles with an aerodynamic diameter of 2.5 μm or less), are harmful to human health (HEI, 2002; Lippmann *et al.*, 2003; Neuberger *et al.*, 2004) and have serious effects on visibility (Jung *et al.*, 2009; Cheng *et al.*, 2011) and global climate change (IPCC, 2007). Recent studies have found that PM<sub>2.5</sub> could not only penetrate into human respiratory and lungs but also influence visibility through the scattering and absorption of solar radiation. Meanwhile, PM plays a

major role in the acidification of precipitation and may affect climate change (Khoder and Hassan, 2008). Nanjing, the capital of Jiangsu province, is an important industrial city and economic center of the Yangtze River delta. Aerosol pollution is becoming increasingly severe with urbanization development. The source apportionment of particulate matter is the basis of the control of air particulate matter pollution. Particles mainly consist of many compounds, such as crust elements, nitrate, sulfate, and various organic species. The dominating primary sources of PM are coal combustion, mobile exhaust, biomass burning and construction dust. It is of great significance to identify contributions to the particulate matter less than 10 μm originating from major sources so that policy makers can develop regional emission control strategies and design efficient governance measures.

The chemical mass balance (CMB) model is one of the most widely used receptor models for source apportionment. The CMB model (Friedlander, 1973; Cooper and Watson, 1980; Watson, 1984; Watson *et al.*, 1984; Gordon, 1988;

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Watson *et al.*, 1990; Hidy and Venkataraman, 1996) consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of source profile abundances and source contributions. Because the CMB model has a clear physical principle, this method has been developed to a mature stage and is generally used by many countries.

Many studies have recently been performed in atmospheric particulate matter source apportionment worldwide. Globally, Chen *et al.* (2010) used the PM<sub>2.5</sub> mass concentration and different types of element, ion and carbon long-term observation data (IMPROVE and STN) with the CMB model for source apportionment in urban and non-urban areas. The largest contribution to secondary inorganic aerosols reached 49%. Deshmukh *et al.* (2011) studied the mass concentration of PM<sub>2.5</sub> and PM<sub>1</sub> and the water-soluble ion mass concentration seasonal variation in Durg City areas in India. Lee (2013) studied the seasonal ion variation and correlation characteristics of size-fractionated particles in the largest industrial city in Korea. Sulfate was the most abundant species in summer, whereas nitrate and ammonium in particles were highest in winter. Choi *et al.* (2013) used the positive matrix factorization (PMF) model for the source apportionment of PM<sub>2.5</sub> in the coastal area of Korea. The major sources were secondary nitrate, secondary sulfate and motor vehicles. He *et al.* (2001) studied the characteristics of PM<sub>2.5</sub> from July 1999 to September 2000 in Beijing, and Song *et al.* (2007) showed the chemical composition and source apportionment of PM<sub>2.5</sub> in Beijing in January and August 2004. Huang *et al.* (2006) and He *et al.* (2006) studied the temporal variation and seasonal characteristics of organic compounds in PM<sub>2.5</sub> in Beijing, the capital of China. The organic aerosol pollution in Beijing was mostly associated with mobile exhaust, coal combustion for residential heating, and cooking emissions. Kong *et al.* (2010) monitored the PM<sub>2.5</sub>, PM<sub>10</sub>, and TSP (total suspended particulates) from June 2007 to February 2008 at a coastal site in Tianjin. The CMB model was applied to identify the source contributions. Coal combustion, marine aerosol, vehicular emission and soil dust explained 5–31%, 1–13%, 13–44% and 3–46% for PM<sub>2.5</sub>, PM<sub>10</sub> and TSP, respectively. Zhang *et al.* (2011) measured the PM<sub>10</sub> data of 220 meteorological towers in Tianjin and analyzed the concentrations of elements, ions and carbons with a chemical mass balance model, identifying different levels of particulate matter source contributions, with the largest contribution from the secondary sulfate (24.11–30.96%), followed by secondary nitrate (16.19–20.95%). Zhang *et al.* (2011) studied the seasonal variations and sources of water-soluble ions in Xi'an PM<sub>2.5</sub>, and the main forms of ions were (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, NH<sub>4</sub>HSO<sub>4</sub>, and NH<sub>4</sub>NO<sub>3</sub>, whose concentration was highest in winter due to coal combustion. These previous studies examined the total PM source apportionment, but also a few studies discussed size-fractionated PM source apportionment. Hu *et al.* (2013) discussed the size distribution of size-fractionated particles and identified four potential sources for PM<sub>2.5</sub> with enrichment factor and principle component analysis methods.

The ultimate aim of this study is using the CMB model to apportion the size-fractionated PM sources at Gulou and

Pukou. This study collected daily aerosol samples from May 2010 to April 2011 at Gulou and Pukou in Nanjing by analyzing the mass concentration and chemical composition, establishing local emission source profiles to use the CMB model to apportion Nanjing size-fractionated particle sources and obtain source contributions. This study has great effects on improving the air quality of Nanjing and providing a scientific basis for governing air pollution in Nanjing.

## MATERIALS AND METHODS

### Sampling Site

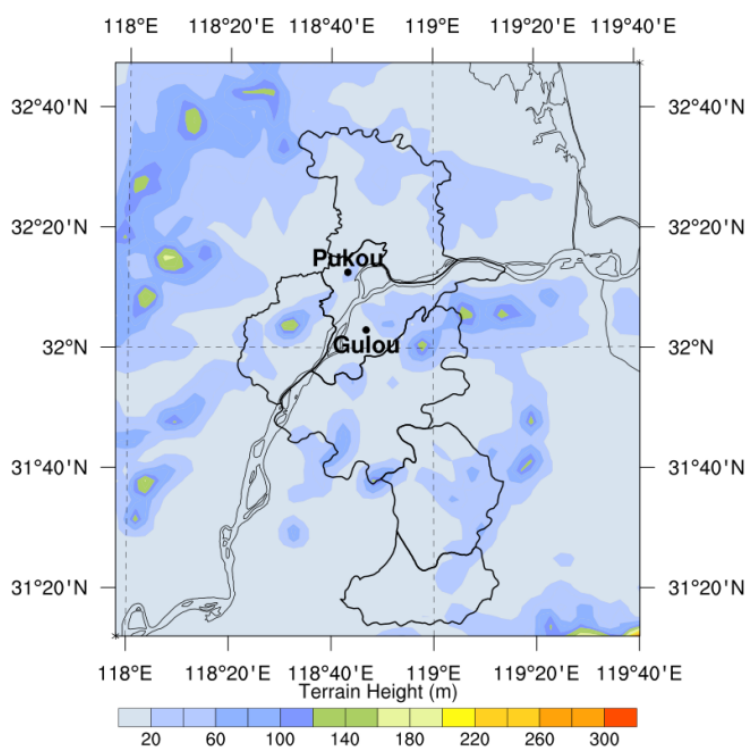
Nanjing (118°22"E and 119°14", 31°14" and 32°37"N) is the capital of Jiangsu province, an important industrial city and economic center in the Yangtze River delta. The size-fractionated PM samples that were used in this study were collected from two sites representing urban and suburban districts in Nanjing. Samples for the downtown area of Nanjing were collected on the roof of an apartment building at the Gulou (118.78°E, 32.05°N) campus of Nanjing University, while the suburban sampling site was located on the roof of a teaching building at the Pukou (118.72°E, 32.21°N) campus of Nanjing University of Information Science & Technology. Fig. 1 shows the two sampling sites in Nanjing.

### Sample Collection

Daily ambient PM measurements were carried out using the Andersen eight-stage cascade impactor (TE-20-800, Tisch, NY, USA), which can classify nine particle size intervals (< 0.43, 0.43–0.65, 0.65–1.1, 1.1–2.1, 2.1–3.3, 3.3–4.7, 4.7–5.8, 5.8–9.0, and 9.0–10 μm), operated at a constant flow rate of 28.3 L min<sup>-1</sup>. A total of 70 daily (based on a 96-h period) samples for four seasons from May 2010 to April 2011 were collected almost every ten days on 81-mm Teflon filters (700 filters, including blank filters) using the cascade impactor. The Gulou site accounted for 35 samples, while the Pukou site accounted for the others. Teflon filters were used for mass determination and the analysis of inorganic ions, crust elements and metal elements. The Teflon filters were equilibrated in a desiccator for 24 h before being weighed to determine the mass. The mass concentrations were measured using a gravimetric analysis with an electronic microbalance with a sensitivity of 0.01 mg.

As an important industrial city in the Yangtze River delta, Nanjing has many enterprises. The pillar industries in Nanjing are electronics, petrochemical, automobile and steel smelting (Hu *et al.*, 2012). Nanjing is one of the most rapidly growing cities in China. The economy has been developing rapidly with a large amount of urban infrastructure and an increase in car ownership. According to the actual situation of Nanjing, the emission sources of atmospheric particles are coal combustion dust, construction dust, smelting dust, soil dust, motor vehicle exhaust, secondary aerosols (mainly sulfate, nitrate and ammonium) and sea salt. The emission sources were collected as follows:

Coal combustion dust: the collecting site was a coal-fired electric utility in a chemical industrial park near the highway. The dust was collected from coal ash sorting



**Fig. 1.** Sampling sites were 1) Gulou campus of Nanjing University (GL) and 2) Pukou campus of Nanjing University of Information Science & Technology (PK).

equipment. Construction dust: ashes were collected at an urban construction site and near the construction site. Smelting dust: a Nanjing steel plant was chosen as a representative sample to collect smelting dust. Ashes were collected outside the blast furnace plant. Soil dust: ashes were collected from the bare soil under a tree at the Nanjing University Gulou campus or from large bare land in a suburban area. Motor vehicle exhaust: to avoid the interference of other sources, motor vehicle exhaust was collected directly by an Andersen cascade impactor at the tailpipe. These kinds of sources were collected in Nanjing locally with specialized approaches such as sweeping or grab sampling of soil, unpaved road, fugitive dust using trowels and brooms. These samples were sieved, resuspended, and size-segregated onto filters using ambient cascade impactors. This method might alter the morphological properties and particle size distribution of the chemical components, but this modification is slightly comparing with other effects (Chow *et al.*, 1994; Watson and Chow, 2001).

The collected ashes were separated by the Andersen cascade impactor on 81-mm high-purity quartz filters. Filters that had been sampled for emission sources were analyzed as same as the ambient sampling filters. Numerous of elemental compositions and ions were determined to make chemical abundances in source profiles.

#### **Sample Treatment and Chemical Analysis**

The collected ambient PM samples and emission sources samples were weighed to determine the aerosol mass. Then, the filters were placed onto clean tinfoil and stored at  $-20^{\circ}\text{C}$  until analysis. The sample filters were divided into

two parts, half for elemental analysis, and half for water-soluble ion analysis.

The elemental analysis of all of the samples was performed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Optima 5300, Perkin-Elmer SCIEX, USA). The concentrations of Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Ti and Zn were determined. The method detection limits (MDLs) were determined by adding 3 standard deviations of the blank readings to the average blank values.

Half of the filter samples were extracted into 20-mL ultrapure water using an ultrasonic bath and a shaker before being measured. The ultrasonic bath was operated for 30 min at  $40^{\circ}\text{C}$ , after which mechanical agitations were performed for 1 h. An ion chromatograph (850 Professional IC-AnCat-MCS) was used to measure  $\text{Cl}^{-}$ ,  $\text{NO}_3^{-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^{+}$ ,  $\text{NH}_4^{+}$ ,  $\text{K}^{+}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions in the aqueous extract. The method detection limit (MDL) was calculated from 1 ppm of the lab-prepared calibration standards. The obtained MDL were 0.01, 0.01, 0.02, 0.01, 0.03, 0.02, 0.01 and 0.01  $\mu\text{g m}^{-3}$  for  $\text{Cl}^{-}$ ,  $\text{NO}_3^{-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^{+}$ ,  $\text{NH}_4^{+}$ ,  $\text{K}^{+}$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , respectively.

#### **CMB Model**

The CMB receptor model consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of the source profile abundances and source contributions. The EPA CMB 8.2 model (US EPA, 2004) uses the effective variance weighted least-squares fitting with both source profiles and ambient concentrations as inputs to be applied to estimate the source contributions and

their uncertainties for individual samples. A brief description of mathematical principle about CMB model is shown below.

$$C_{it} = \sum_{i=1}^N F_{in} S_{nt} + E_{it} \quad (1)$$

In the formula above  $C_{it}$  represents ambient concentration of the  $i$ -th chemical species measured at time  $t$ . It is equal to the sum of contributions from all the sources  $N$  in theory.  $F_{in}$  is the fractional abundance (source profile) of the  $i$ -th species in the  $n$ -th source type.  $S_{nt}$  is the mass contribution of  $n$ -th source at time  $t$ .  $E_{it}$  represents the difference between the measured and estimated ambient concentration.

The measured uncertainties (UNC) of all of the samples and blanks were estimated as follows:

$$UNC = \sqrt{\left(\frac{MDL}{3}\right)^2 + (P \times Conc)^2} \quad (2)$$

where  $P$  is a concentration-dependent precision, 7.1% for all species without Na 9.8%, Mg 8.5%, or Al 8.6% (Baumann *et*

*al.*, 2008; Kim *et al.*, 2005).

## RESULTS AND DISCUSSION

### PM Concentrations

A total of 70 daily samples of size-fractionated PM were collected from May 2010 to April 2011 at two sites in Nanjing. The concentrations of  $PM_{10}$ ,  $PM_{2.1}$ , and  $PM_{1.1}$  and the  $PM_{2.1}/PM_{10}$  ratio in Nanjing are shown in Table 1.

The daily  $PM_{10}$  concentration ranged from 37 to 290  $\mu\text{g m}^{-3}$  at Gulou and 45 to 375  $\mu\text{g m}^{-3}$  at Pukou. The annual average  $PM_{10}$  mass concentration was  $135.8 \pm 66.4 \mu\text{g m}^{-3}$  at Gulou and  $132.2 \pm 73.0 \mu\text{g m}^{-3}$  at Pukou, with negligible differences between the two sites. The annual average  $PM_{2.1}$  mass concentration and standard deviation (SD) were  $55.1 \pm 36.3 \mu\text{g m}^{-3}$  and  $64.8 \pm 40.2 \mu\text{g m}^{-3}$  at Gulou and Pukou, respectively. The data show significant differences in that the  $PM_{2.1}$  concentration is greater at Pukou than at Gulou. The annual average  $PM_{1.1}$  mass concentration and standard deviation (SD) were  $39.4 \pm 23.0 \mu\text{g m}^{-3}$  and  $45.5 \pm 34.6 \mu\text{g m}^{-3}$  at Gulou and Pukou, respectively. The  $PM_{1.1}$  difference between urban and suburban sites was the same as that of

**Table 1.** Concentrations ( $\mu\text{g m}^{-3}$ ) of  $PM_{10}$ ,  $PM_{2.1}$  and  $PM_{1.1}$  and ratios of  $PM_{2.1}/PM_{10}$  at Gulou(GL) and Pukou(PK) in Nanjing.

Season	Site	Type	Statistics ( $\mu\text{g m}^{-3}$ )					Ratio
			N <sup>a</sup>	Max	Min	Mean	SD <sup>b</sup>	
Spring	GL	$PM_{10}$	10	270.4	92.2	153.7	57.4	0.38
		$PM_{2.1}$	10	119.9	36.3	58.1	29.6	
		$PM_{1.1}$	10	93.2	28.1	44.5	21.9	
	PK	$PM_{10}$	9	208.9	74.9	121.9	41.6	0.52
		$PM_{2.1}$	9	120.0	42.3	62.8	23.7	
		$PM_{1.1}$	9	89.4	30.5	46.1	18.7	
Summer	GL	$PM_{10}$	8	101.5	37.1	65.2	22.2	0.40
		$PM_{2.1}$	8	36.0	13.3	26.0	9.4	
		$PM_{1.1}$	8	29.4	10.6	21.1	7.5	
	PK	$PM_{10}$	6	91.3	67.0	75.9	9.8	0.49
		$PM_{2.1}$	6	43.7	33.6	37.5	3.6	
		$PM_{1.1}$	6	34.0	23.1	28.6	4.2	
Autumn	GL	$PM_{10}$	9	261.9	60.9	129.7	64.0	0.39
		$PM_{2.1}$	9	95.8	18.8	50.0	22.3	
		$PM_{1.1}$	9	77.0	14.5	36.7	17.3	
	PK	$PM_{10}$	9	376.0	45.8	155.5	111.0	0.39
		$PM_{2.1}$	9	96.3	22.7	60.4	25.3	
		$PM_{1.1}$	9	70.7	17.2	40.0	18.7	
Winter	GL	$PM_{10}$	9	290.0	134.0	184.7	54.2	0.45
		$PM_{2.1}$	9	196.0	40.4	82.8	49.6	
		$PM_{1.1}$	9	118.9	29.3	54.4	28.4	
	PK	$PM_{10}$	9	256.9	79.4	156.8	58.6	0.57
		$PM_{2.1}$	9	236.5	46.4	89.6	63.1	
		$PM_{1.1}$	9	215.6	28.9	61.7	59.4	
Annual	GL	$PM_{10}$	36	290.0	37.1	135.8	66.4	0.41
		$PM_{2.1}$	36	196.0	13.3	55.1	36.3	
		$PM_{1.1}$	36	118.9	10.6	39.4	23.0	
	PK	$PM_{10}$	33	376.0	45.8	132.2	73.0	0.49
		$PM_{2.1}$	33	236.5	22.7	64.8	40.2	
		$PM_{1.1}$	33	215.6	17.2	45.5	34.6	

<sup>a</sup>Number of samples.

<sup>b</sup>Standard deviation.

PM<sub>2.1</sub>. Because there is no 2.5- $\mu\text{m}$  cut-point of the Andersen cascade impactor sampler, 2.1  $\mu\text{m}$  is defined as the boundary between fine and coarse particles in this study. Referring to the latest Ambient Air Quality Standards (GB3095-2012) annual average of PM<sub>2.5</sub> in China (35  $\mu\text{g m}^{-3}$ ), the PM<sub>2.1</sub> mass concentrations were overweight at both sites and were much higher than the annual average of 12  $\mu\text{g m}^{-3}$  for USA National Ambient Air Quality Standard (NAAQS) for PM<sub>2.5</sub>. But the PM<sub>2.1</sub> concentration in Nanjing was lower than that in other mega cities in China but much higher than that in the USA and other countries (Table 2).

Similar seasonal variations in the PM concentrations were observed at two sites. The seasonal variations of size-fractionated PM were winter > spring > autumn > summer at both sites except for that of PM<sub>10</sub> at Pukou, which was winter > autumn > spring > summer. The maximum mass concentration in winter was approximately twice higher than the minimum mass concentration in summer at both sites. The high concentration in winter was most likely due to the stable meteorological condition that limited the dispersion and the reduced amount of surface vegetation that made it easier for dust to mix with the air. And the increased coal burning emissions due to space heating also made the PM concentration higher in winter. The low concentration in summer was likely because of high-frequency precipitation and precipitation rate that removed particles through rainout or washout processes.

The annual average PM<sub>2.1</sub>/PM<sub>10</sub> ratio was 0.41 and 0.49 at Gulou and Pukou, respectively. The PM<sub>2.1</sub>/PM<sub>10</sub> seasonal variation ranged from 0.38 to 0.57. The ratio of PM<sub>2.1</sub>/PM<sub>10</sub> was lower than that of many other countries, for instance, 0.54 in Ulsan, Korea (Lee and Hieu, 2013) and 0.59 in Navarra, Spain (Aldabe *et al.*, 2011). The annual average value of PM<sub>2.1</sub>/PM<sub>10</sub> at Pukou was higher than that at Gulou possibly due to construction dust. Nanjing has carried out a large number of urban construction in order to hold the Asian Youth Games and Youth Olympic Games. So an excessive number of construction sites in the urban area produced building dust with particulates of coarse diameter (PM<sub>10-2.1</sub>), leading to a lower value of PM<sub>2.1</sub>/PM<sub>10</sub> at Gulou which is on behalf of urban area. Meanwhile, a large concentration of iron, steel smelting, petroleum and chemical enterprises around the Pukou site may have produced a large amount of coal combustion dust, smelting dust and secondary aerosols, which are mostly fine particulate matter. Therefore, the value of PM<sub>2.1</sub>/PM<sub>10</sub> at Pukou is higher.

Fig. 2 shows the size-fractionated particulate concentration variations at Gulou and Pukou as measured by an Andersen eight-stage cascade impactor during the study period. The size distribution of the particulate concentration is different. The PM at Gulou showed a distinct distribution with a strong peak of 5.8–10  $\mu\text{m}$  and a weak peak of 0.65–1.1  $\mu\text{m}$ . The PM at Pukou showed significant double-hump distribution with strong peaks of 5.8–9.0  $\mu\text{m}$  and 1.1–2.1  $\mu\text{m}$ . This study shows that the average concentration of coarse particles (PM<sub>10</sub>–PM<sub>2.1</sub>) is higher at Gulou than at Pukou. The increased concentration of coarse particles would be caused by the contribution of soil and construction dust with relatively dry and windy meteorological conditions.

**Table 2.** Mass concentrations ( $\mu\text{g m}^{-3}$ ) of fine particles and the major ions at different sites over the world (The cut-sizes of fine particles are 2.5  $\mu\text{m}$  for other works compared to 2.1  $\mu\text{m}$  in this work).

Site	Time	Mass	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Na <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Reference
GL, Nanjing, China	2010–2011	55.1	1.89	9.07	12.01	0.35	4.51	0.70	1.16	0.14	This work
PK, Nanjing, China	2010–2011	64.8	2.07	7.32	10.78	0.45	4.07	0.81	0.91	0.15	This work
Beijing, China	1999–2000	127	NR <sup>a</sup>	9.90	14.08	NR	6.51	NR	2.21	NR	He <i>et al.</i> (2001)
Beijing, China	2001–2003	154.3	3.07	11.52	17.07	0.55	8.72	1.63	1.55	0.17	Wang <i>et al.</i> (2005)
Shanghai, China	2003–2005	94.6	3.00	6.23	10.39	0.57	3.78	1.25	0.63	0.28	Wang <i>et al.</i> (2006)
Qingdao, China	1997–2000	43.6	0.83	3.40	11.94	1.48	5.79	0.52	2.27	0.52	Hu <i>et al.</i> (2002)
Fuzhou, China	2007–2008	44.33	1.55	4.40	10.78	0.64	3.89	0.38	0.23	0.09	Xu <i>et al.</i> (2012)
Denver, USA	2002–2003	8.50	NR	0.96	1.15	NR	0.55	NR	NR	NR	Dutton <i>et al.</i> (2010)
Seoul, Korea	2009–2010	38.09	1.16	3.21	4.13	0.89	3.15	NR	0.47	NR	Choi <i>et al.</i> (2013)
Navarra, Spain	2009	15.38	0.08	1.63	2.04	NR	1.24	NR	NR	NR	Aldabe <i>et al.</i> (2011)

<sup>a</sup>Not reported.

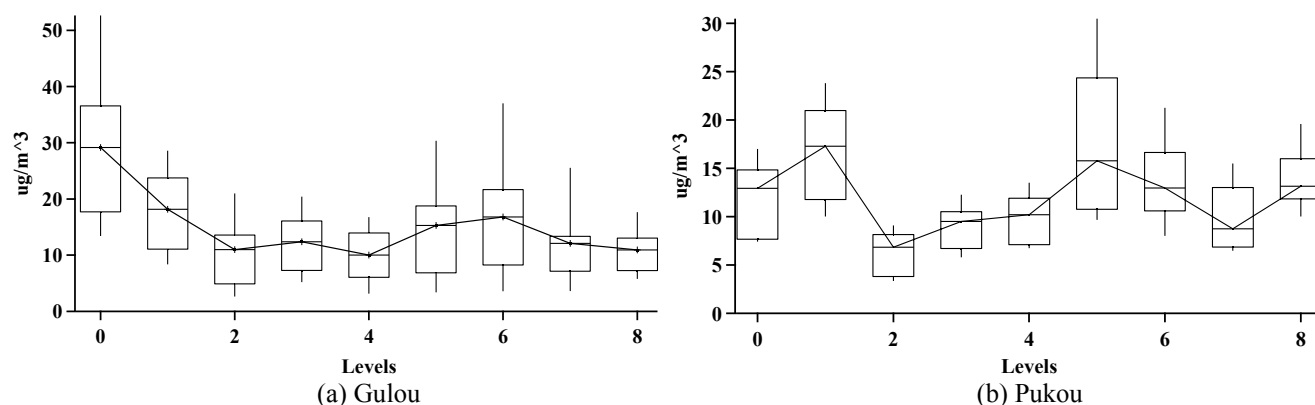


Fig. 2. Size-fractionated particulate concentration variations at (a) Gulou (b) Pukou.

### Concentration of Chemical Species

A total of 17 types of chemical elements and 8 types of water-soluble ions concentrations were detected in this study. The crustal materials, such as [Al, Ca, Fe and Ti], were calculated as follows, intending to account for unmeasured mineral oxides:

$$\text{Crustal material} = 2.2 \times [\text{Al}] + 1.63 \times [\text{Ca}] + 2.42 \times [\text{Fe}] + 1.94 \times [\text{Ti}]$$

The average concentration of all of the chemical compositions in PM<sub>10</sub> is 67.17  $\mu\text{g m}^{-3}$  at the Gulou site and 61.3  $\mu\text{g m}^{-3}$  at the Pukou site with the exceptions of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , accounting for average PM<sub>10</sub> concentrations of 49.5% and 43.8% at Gulou and Pukou, respectively. The chemical composition concentration in PM<sub>2.1</sub> is 35.11  $\mu\text{g m}^{-3}$  and 35.61  $\mu\text{g m}^{-3}$ , accounting for an average PM<sub>2.1</sub> concentration of 63.7% and 49.7% at Gulou and Pukou, respectively. The annual average concentrations of chemical species in PM<sub>2.1</sub> and PM<sub>10</sub> at the two sites are shown in Fig. 3.

In PM<sub>10</sub>, the concentrations of the major abundant chemical compositions follow the order  $\text{SO}_4^{2-} > \text{NO}_3^- > \text{Ca} > \text{NH}_4^+ > \text{Cl}^- > \text{Fe} > \text{Al} > \text{K} > \text{Mg}$ , while the decreasing sequence in PM<sub>2.1</sub> is  $\text{SO}_4^{2-} > \text{NO}_3^- > \text{NH}_4^+ > \text{Cl}^- > \text{K} > \text{Fe} > \text{Ca} > \text{Zn} > \text{Na} > \text{Al}$ . In PM<sub>10</sub>, the dominant chemical compositions account for 93.02% and 91.56% at Gulou and Pukou, respectively, for all of the measured compositions; meanwhile, in PM<sub>2.1</sub>, these compositions account for 95.23% and 93.48% at Gulou and Pukou, respectively. The remaining chemical components are present in too low of a concentration to be listed. Comparing the chemical composition concentration of PM<sub>2.1</sub> to those of PM<sub>10</sub>, the concentration of calcium significantly decreased, suggesting that calcium makes a large contribution to coarse particles. The concentrations of major ions slightly decreased, indicating that the contribution of water-soluble ions is focused in fine particles.

Water-soluble ions play an important role in the atmosphere and take large proportions of particulate matter, especially fine particles. In PM<sub>10</sub>, the mass concentrations of the total ions that were measured in this work contribute an average of 33.4% and 29.1% at Gulou and Pukou, respectively, while in PM<sub>2.1</sub>, the contributions are 54.1% and 41.0%,

respectively.

The mass concentrations of PM<sub>2.1</sub> and the major ions in different locations worldwide are shown in Table 2. PM<sub>2.1</sub> in this study is compared to PM<sub>2.5</sub> in other studies for convenience, even though there is a slight difference in the values between PM<sub>2.1</sub> and PM<sub>2.5</sub>. The fine particulate concentrations in this study in Nanjing are lower than those in mega cities in China but higher than those in the same urban-size cities in China and much higher than those in the USA, Spain and Korea, indicating that particle pollution is serious in Nanjing. The concentrations of  $\text{SO}_4^{2-}$  and  $\text{NH}_4^+$  are in the same magnitude (approximately 10  $\mu\text{g m}^{-3}$  and 3–5  $\mu\text{g m}^{-3}$ , respectively) as those of other cities in China except for those in Beijing (approximately 15  $\mu\text{g m}^{-3}$  and 6–8  $\mu\text{g m}^{-3}$ , respectively). The concentration of  $\text{NO}_3^-$  is lower than that in Beijing but higher than that in other cities in China, indicating that secondary inorganic aerosols play an important role in Nanjing particulate pollution with a high concentration of sulfate and nitrate in a relatively low PM<sub>2.1</sub> mass concentration.

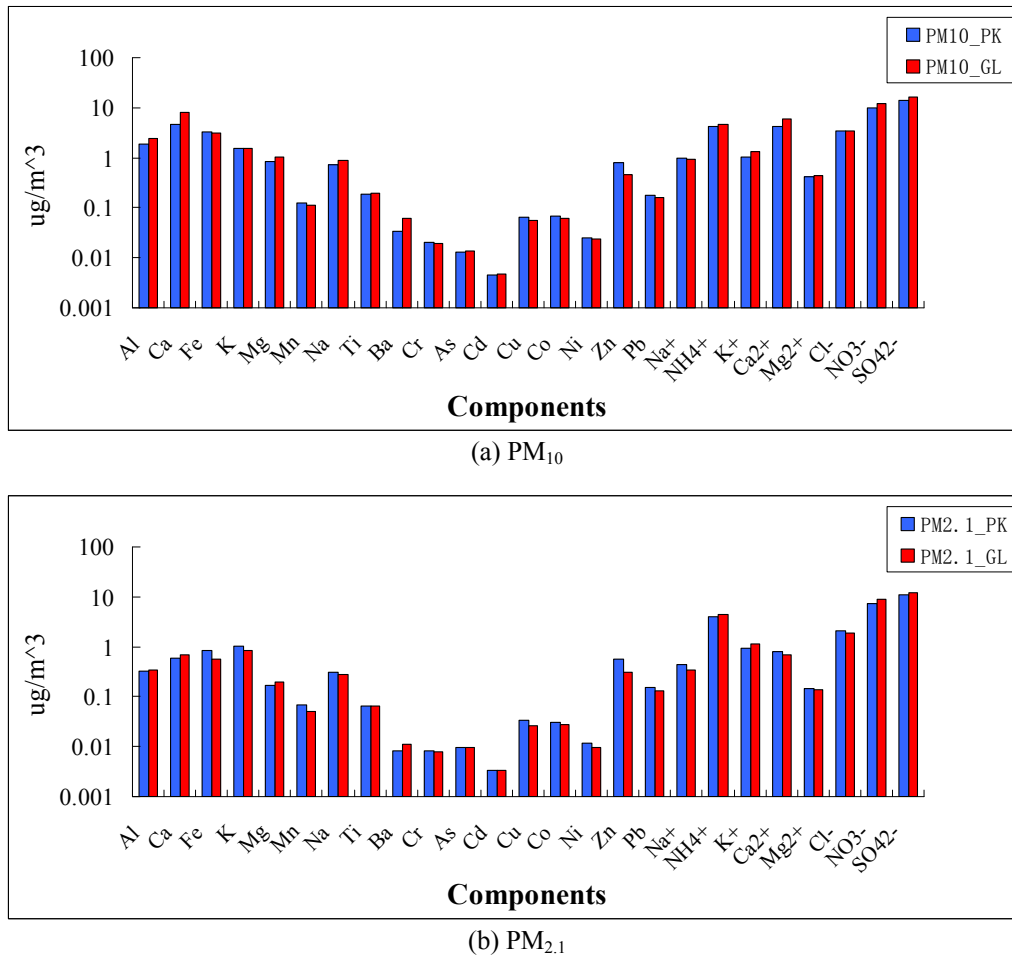
The average annual concentrations of the size-fractionated PM major chemical compositions at Gulou and Pukou in Nanjing are shown in Tables 3 and 4. The concentration of  $\text{Ca}^{2+}$  decreases with particulate size. In contrast, the concentrations of other ions increase with the decreased particulate size. The PM<sub>2.1</sub>/PM<sub>10</sub> ratio of  $\text{Ca}^{2+}$  at the Gulou site was 11.6%, and the ratios of  $\text{Na}^+$  and  $\text{Mg}^{2+}$  were approximately 30%.  $\text{Na}^+$  and  $\text{Mg}^{2+}$  were the main components of sea salt aerosols, suggesting that sea salt aerosols mainly contribute to coarse particles. The ratios of  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ , and  $\text{NH}_4^+$  were approximately 70%, 70%, and 95%, respectively, confirming that the contribution of secondary aerosols is mainly concentrated in fine particles. An analysis of the Pukou site also reached the same results.

Through the correlation analysis of water-soluble ions at the Gulou site, we found that  $\text{Na}^+$  and  $\text{Cl}^-$  at levels 0–4 had a high correlation ( $R$  was 0.932, 0.900, 0.847, 0.891, and 0.593, respectively), indicating that these two ions may have the same emission source. Considering that NaCl is the main component of sea salt, sea salt aerosol should be considered an emission source in coarse particles.

At levels 0 and 3–5,  $\text{K}^+$  and  $\text{SO}_4^{2-}$  had a high correlation ( $R$  was 0.765, 0.766, 0.851, and 0.921, respectively). The

high correlation in coarse particles maybe indicating that they are belong to the particles from sea salts.  $K^+$  and  $NH_4^+$  had a high correlation at levels 2–5 (R was 0.798, 0.816,

0.815, 0.784, respectively), indicating that a small part of the  $NH_4^+$  in the coarse particles may come from biomass burning (Tsai *et al.*, 2012).



**Fig. 3.** Annual average concentrations of chemical species in (a)  $PM_{10}$  and (b)  $PM_{2.1}$  at Gulou (GL) and Pukou (PK).

**Table 3.** Average annual concentrations ( $\mu g m^{-3}$ ) of size-fractionated PM major chemical compositions at Gulou.

Species	0 level	1 level	2 level	3 level	4 level	5 level	6 level	7 level	8 level
	PM size range ( $\mu m$ )								
	10–9.0	9.0–5.8	5.8–4.7	4.7–3.3	3.3–2.1	2.1–1.1	1.1–0.65	0.65–0.43	< 0.43
Al	0.5867	0.4479	0.3350	0.3660	0.2818	0.1901	0.0690	0.0423	0.0453
Ca	2.6546	1.7762	1.1146	1.0802	0.6804	0.3082	0.1332	0.1134	0.1240
Fe	0.7488	0.5638	0.4336	0.4406	0.3656	0.2613	0.1461	0.0962	0.0704
K	0.1758	0.1385	0.1137	0.1370	0.1278	0.2053	0.2623	0.1990	0.1715
Mg	0.2463	0.1824	0.1304	0.1487	0.1157	0.0961	0.0480	0.0230	0.0260
Na	0.1321	0.1203	0.0910	0.1364	0.1226	0.1176	0.0790	0.0470	0.0423
Ti	0.0315	0.0289	0.0254	0.0223	0.0228	0.0191	0.0164	0.0126	0.0175
Zn	0.0221	0.0207	0.0192	0.0347	0.0628	0.1358	0.0884	0.0442	0.0341
$Na^+$	0.1127	0.1341	0.0801	0.1548	0.1215	0.1185	0.0999	0.0625	0.0678
$NH_4^+$	0.0280	0.0170	0.0261	0.0307	0.1190	0.9990	1.4523	1.1446	0.9111
$K^+$	0.0333	0.0263	0.0213	0.0380	0.0531	0.2792	0.3847	0.2735	0.2211
$Ca^{2+}$	1.6687	1.3920	0.7716	0.9490	0.5813	0.2676	0.1922	0.1116	0.1288
$Mg^{2+}$	0.0726	0.0593	0.0389	0.0706	0.0482	0.0564	0.0453	0.0203	0.0191
$Cl^-$	0.3280	0.3197	0.2066	0.3330	0.2919	0.5346	0.5570	0.4155	0.3808
$NO_3^-$	0.6445	0.5818	0.4231	0.7726	0.8775	2.3945	3.0111	2.2241	1.4465
$SO_4^{2-}$	0.7410	0.6790	0.9785	0.8141	0.9045	2.7785	3.6537	2.6357	2.9412

**Table 4.** Average annual concentrations ( $\mu\text{g m}^{-3}$ ) of size-fractionated PM major chemical compositions at Pukou.

Species	0 level	1 level	2 level	3 level	4 level	5 level	6 level	7 level	8 level
	PM size range ( $\mu\text{m}$ )								
	10–9.0	9.0–5.8	5.8–4.7	4.7–3.3	3.3–2.1	2.1–1.1	1.1–0.65	0.65–0.43	<0.43
Al	0.3429	0.4512	0.1927	0.2792	0.2986	0.1916	0.0668	0.0304	0.0334
Ca	0.9875	1.3268	0.5319	0.6809	0.6088	0.3141	0.1382	0.0823	0.0670
Fe	0.5441	0.7010	0.3481	0.4194	0.4610	0.3839	0.2336	0.1309	0.1056
K	0.1010	0.1352	0.0724	0.0977	0.1167	0.2246	0.2797	0.2147	0.2904
Mg	0.1408	0.1899	0.0853	0.1145	0.1258	0.0934	0.0381	0.0209	0.0190
Na	0.0498	0.1046	0.0614	0.0976	0.1170	0.1343	0.0766	0.0434	0.0520
Ti	0.0281	0.0314	0.0190	0.0219	0.0220	0.0194	0.0150	0.0143	0.0169
Zn	0.0221	0.0330	0.0222	0.0456	0.1208	0.2615	0.1626	0.0682	0.0583
Na <sup>+</sup>	0.0664	0.1226	0.0708	0.1308	0.1419	0.1435	0.1408	0.0766	0.0850
NH <sub>4</sub> <sup>+</sup>	0.0169	0.0149	0.0231	0.0351	0.0854	0.8969	1.2916	0.8645	1.0176
K <sup>+</sup>	0.0103	0.0173	0.0095	0.0219	0.0350	0.1808	0.2654	0.1993	0.2683
Ca <sup>2+</sup>	0.7597	1.0116	0.4311	0.5827	0.5382	0.2485	0.2794	0.1249	0.1531
Mg <sup>2+</sup>	0.0492	0.0734	0.0308	0.0596	0.0578	0.0555	0.0517	0.0172	0.0236
Cl <sup>-</sup>	0.2073	0.2975	0.1877	0.2888	0.3197	0.5813	0.6198	0.3647	0.5053
NO <sub>3</sub> <sup>-</sup>	0.3150	0.4557	0.4262	0.6707	0.8325	2.0505	2.3468	1.4347	1.4849
SO <sub>4</sub> <sup>2-</sup>	0.5243	0.7417	0.3593	0.6229	0.9995	3.5086	6.2032	3.7805	3.2269

At levels 5–7, there was a high correlation between SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> (*R* was 0.831, 0.751 and 0.701, respectively). Because these compounds are transformed from SO<sub>2</sub> and NO<sub>x</sub>, the high correlation suggests that they come from the same air mass and also possibly the same emission sources or the same source regions. NH<sub>4</sub><sup>+</sup> had a good correlation with both SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup>, as the correlation coefficient *R*<sup>2</sup> between NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> from levels 5 to 8 were 0.956, 0.888, 0.952 and 0.807, respectively. *R*<sup>2</sup> was 0.945, 0.865 and 0.857, respectively, from levels 5–7 between NH<sub>4</sub><sup>+</sup> and SO<sub>4</sub><sup>2-</sup>. The correlation of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> was better than that of SO<sub>4</sub><sup>2-</sup>.

Comparisons between the calculated and observed NH<sub>4</sub><sup>+</sup> concentrations were conducted to evaluate the formation of ions (Cheng *et al.*, 2011). The NH<sub>4</sub><sup>+</sup> concentration can be calculated based on the stoichiometric ratios of the major compounds (i.e., ammonium sulfate [(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>], ammonium bisulfate [NH<sub>4</sub>HSO<sub>4</sub>] and ammonium nitrate [NH<sub>4</sub>NO<sub>3</sub>]) assuming that NO<sub>3</sub><sup>-</sup> is in the form of NH<sub>4</sub>NO<sub>3</sub> and that SO<sub>4</sub><sup>2-</sup> is in the form of either NH<sub>4</sub>HSO<sub>4</sub> or (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Fig. 4 shows the good correlation between the calculated and measured NH<sub>4</sub><sup>+</sup> concentrations at the Gulou site. The slope when NH<sub>4</sub>HSO<sub>4</sub> was assumed was closer to 1 than that when (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> was assumed, suggesting that aerosol was in the form of NH<sub>4</sub>HSO<sub>4</sub>.

#### Characteristics of the Size-Fractionated PM Source Profiles in Nanjing

Coal combustion dust, smelting dust, building dust, soil dust, vehicle exhaust, secondary aerosols and sea salt have been classified as the emission sources according to the actual situation in Nanjing. The source profiles consist of the measured mass fractions (abundances) of chemical components in size-fractionated PM emissions from different source types. Through a correlation analysis, the compositions of secondary aerosol water-soluble ions were determined. Secondary inorganic aerosols were represented by pure

ammonium nitrate (AMNIT; NH<sub>4</sub>NO<sub>3</sub>) and ammonium bisulfate (AMSUL; NH<sub>4</sub>HSO<sub>4</sub>). Sea salt aerosol was represented by a profile containing exclusively (100%) NaCl.

The main chemical composition of coal combustion dust was Al. The three most common elements in PM<sub>10</sub> were Al (9.107%), Fe (2.745%), and Ca (1.572%), and the two most common elements in PM<sub>2.5</sub> were Al (8.208%) and Fe (0.850%). The proportion of chemical components of coal combustion dust is small, probably because the main chemical component in coal combustion dust is the residual carbon due to incomplete combustion. Therefore, the OC and EC requires further analysis.

The main chemical composition of smelting dust was Fe. The three most common elements were Fe (26.458%), Ca (5.479%), and Al (3.757%) in PM<sub>10</sub> and Fe (10.697%), Mg (5.741%), and Al (3.930%) in PM<sub>2.5</sub>. The high Fe content was due to the smelting dust that was collected from the Nanjing steel plant.

The main chemical composition of construction dust was Al. The three most common elements were Al (4.162%), Ca (3.647%), and Fe (3.217%) in PM<sub>10</sub>, which have similar percentages. The three most common components were Al (19.095%), Mg (5.031%), and SO<sub>4</sub><sup>2-</sup> (3.920%) in PM<sub>2.5</sub>. The chemical composition of cement affected the composition of building dust. Cement was mainly composed of CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and SO<sub>4</sub>. In addition, a limited amount of calcium sulfate (CaSO<sub>4</sub>) is often added as an additive to Portland-type cement. Without an analysis of the element Si, then Al, Ca and Fe are the main components.

The three elements that accounted for the largest proportion of vehicle exhaust source in PM<sub>10</sub> were Al (6.095%), Ca (2.050%) and Mg (1.234%); the proportions in PM<sub>2.5</sub> were Al (9.108%), Ca (3.016%) and Mg (1.530%), respectively. The total mass concentration in the chemical composition was very small. Because of carbon dioxide, which was not measured, and water, these were the main components of automobile tailpipe emissions. Other pollutants such as



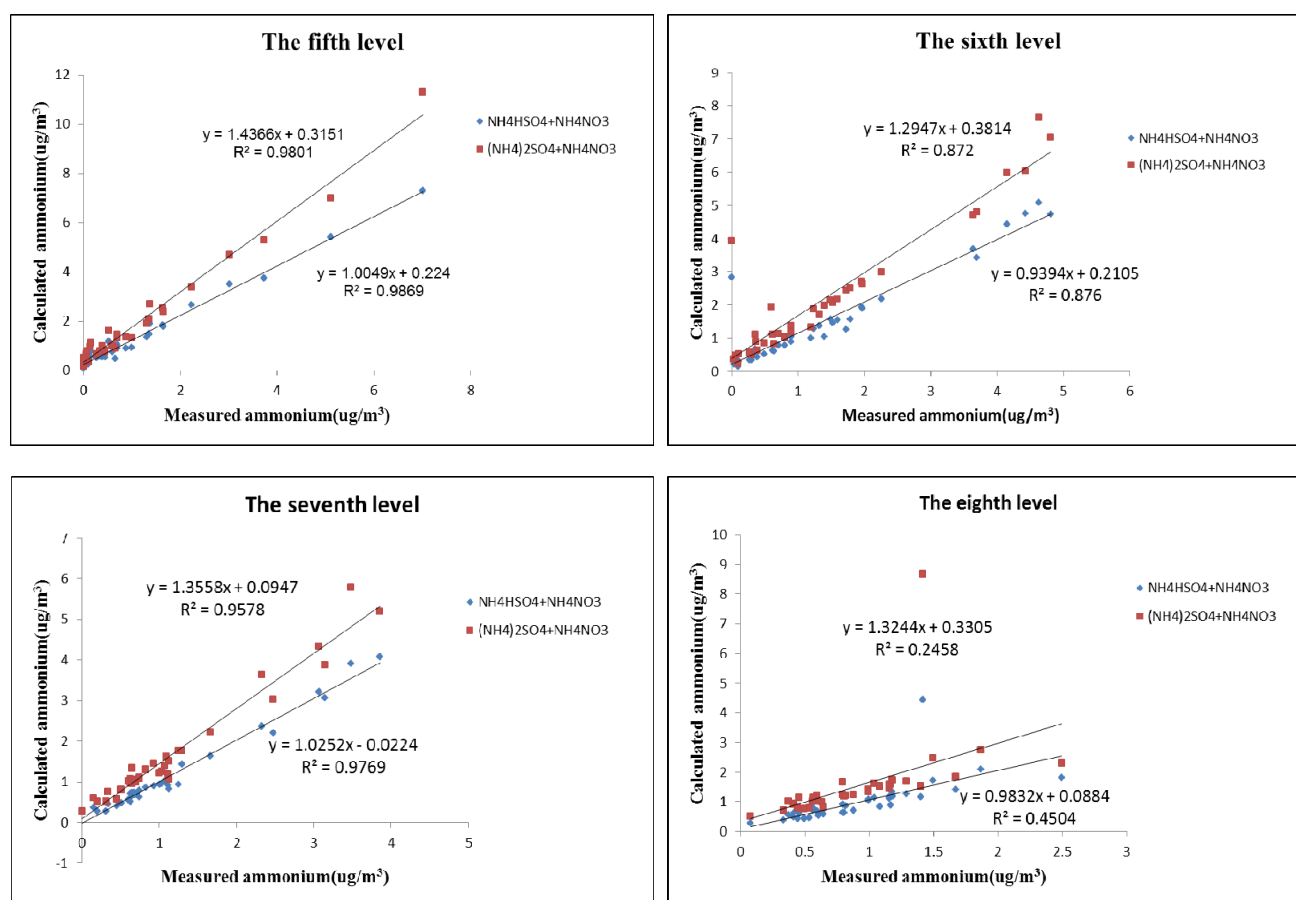


Fig. 4. Comparison of calculated and measured ammonium at levels 5–8.

soot, sulfur dioxide, carbon monoxide, nitrogen oxides and volatile hydrocarbons, most of which were in gaseous form, were not collected.

The main chemical composition of soil dust was Al. The three most common elements were Al (13.179%), Ca (11.970%), and Fe (3.980%) in PM<sub>10</sub> and Al (15.923%), Ca (6.615%), and Mg (2.846%) in PM<sub>2.1</sub>. The soil dust represents the crust element content. Without the detection of Si, then Al, Ca and Fe are the main components of soil dust.

#### Size-Fractionated Source Apportionment in Nanjing

Table 5 shows the size-fractionated source apportionment results at the Gulou and Pukou sites. The source contributions at the two sites were slightly different. Construction dust was the largest emission source at coarse particles both at the urban (Gulou) and suburban (Pukou) sites. The construction dust proportion at Pukou (47.26%) was lower than that at Gulou (58.92%) indicating that a large number of construction sites in urban areas made the dust contribution higher at Gulou.

The smelting dust was the second largest emission source at PM<sub>10–2.1</sub> at both sites. However smelting dust at Pukou (19.67%) contributed higher than that at Gulou (14.08%). This was because that a large number of smelting enterprises in suburban areas made the smelting dust contribution higher at Pukou.

The third largest emission source was soil dust at both

sites but at Gulou site the vehicle exhaust (8.09%) was slightly lower than soil dust (8.12%) indicating that vehicle exhaust should be more influential at urban at coarse particles. Moreover, farmland and large bare areas in the suburban area lead to greater soil dust emission at Pukou (8.56%). The sea salt dust also made important contributions to coarse particles. We can preliminarily conclude that sea salt particles are mainly distributed from 9.0 to 2.1 μm. The contributions were roughly the same at two sites. The vehicle exhaust made very different contributions at Gulou (8.09%) and Pukou (4.06%) at coarse particles indicating a much heavier traffic in the urban area.

The main emission sources at PM<sub>2.1</sub> were secondary inorganic aerosols and coal combustion dust. The source contributions were consistent at the two sites. The secondary aerosols made the largest contribution at two sites. The sum of sulfates and nitrates can account for 58.76% and 44.23% at Gulou and Pukou, respectively, followed by coal combustion, which accounts for 15.87% and 39.46%, respectively. The proportion of secondary inorganic aerosols at Gulou was higher than that at Pukou, especially nitrate aerosols. The nitrate aerosols contributed much higher at Gulou (28.05%) than Pukou (17.39%). Because nitrate aerosol mainly comes from vehicle emissions of NO<sub>x</sub>, and the proportion of vehicle exhaust at Gulou is higher than that at Pukou, the vehicle exhaust had a greater contribution in urban areas than in suburban areas.

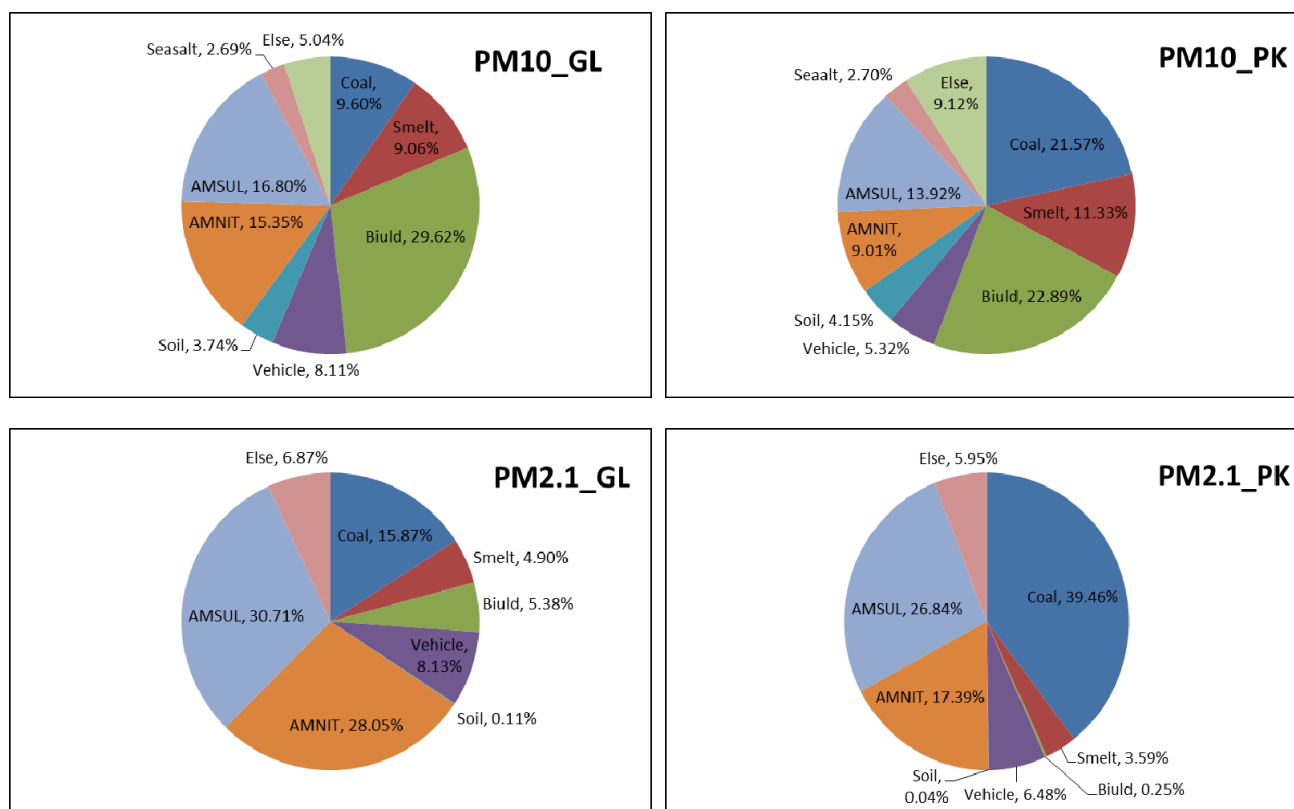
**Table 5.** The size-fractionated source apportionment (%) at Gulou (a) and Pukou (b).

		coal	smelt	const	vehicle	soil	AMNIT	AMSUL	seasalt	other
GL	PM <sub>10</sub>	9.60	9.06	29.62	8.11	3.74	15.35	16.80	2.69	5.04
	PM <sub>10-2.1</sub> <sup>a</sup>	2.02	14.08	58.92	8.09	8.12	-	-	5.93	2.84
	PM <sub>2.1</sub>	15.87	4.90	5.38	8.13	0.11	28.05	30.71	-	6.87
	PM <sub>1.1</sub>	24.81	0.14	12.90	2.18	0.26	31.58	28.13	-	-

<sup>a</sup> Sum of 0–4 levels (10–2.1 μm).

		coal	smelt	const	vehicle	soil	AMNIT	AMSUL	seasalt	other
PK	PM <sub>10</sub>	21.57	11.33	22.89	5.32	4.15	9.01	13.92	2.70	9.12
	PM <sub>10-2.1</sub> <sup>a</sup>	2.31	19.67	47.26	4.06	8.56	-	-	5.62	12.52
	PM <sub>2.1</sub>	39.46	3.59	0.25	6.48	0.04	17.39	26.84	-	5.95
	PM <sub>1.1</sub>	64.08	0.26	0.47	1.11	0.08	11.21	22.79	-	-

<sup>a</sup> Sum of 0–4 levels (10–2.1 μm).

**Fig. 5.** Pie chart of source contributions at the two sites.

The second largest emission source was coal combustion dust. The proportion of coal combustion dust was higher at Pukou (39.46%) than Gulou (15.87%). It was because of there was a large-scale power plant near Pukou sites and there was no power plant in the urban areas.

The third largest emission source was vehicle exhaust at both sites. The vehicle exhaust contributed higher at Gulou (8.13%) than Pukou (6.48%) indicating a heavier traffic at urban areas. Due to a lack of the component analysis of OC/EC in the results, the vehicle exhaust emission source contribution in this study was on the low side, and a higher nitrate contribution can be seen as the contribution of

automobile exhaust after secondary transformation.

The contribution of each source for PM<sub>10</sub> is shown in Fig. 5. The total contribution of PM<sub>10</sub> emission source at Gulou was 94.96%, and the contributions of the first three sources were building dust (29.62%), sulfate (16.80%) and nitrate (15.35%). The total contribution of the PM<sub>10</sub> emission source at Pukou was 90.88%, and the contributions of the first three sources were building dust (22.89%), coal combustion dust (21.57%) and sulfate (15.35%). The total contribution of the PM<sub>2.1</sub> emission source at Gulou was 93.13%, and the contributions of the first three sources were sulfate (30.71%), nitrate (28.05%) and coal combustion

dust (15.87%). The total contribution of the PM<sub>2.1</sub> emission source at Pukou was 94.05%, and the contributions of the first three sources were coal combustion dust (39.46%), sulfate (26.84%), and nitrate (17.39%).

## CONCLUSIONS

The size-fractionated PM samples that were collected at the Gulou and Pukou sites in Nanjing during the period from May 2010 to April 2011 were analyzed. The mass concentrations, chemical compositions and source apportionment of the size-fractionated PM at the two sites were investigated. The source contributions were identified using the chemical mass balance (CMB) model.

The annual mean PM<sub>10</sub> concentrations were  $135.8 \pm 66.4 \mu\text{g m}^{-3}$  and  $132.2 \pm 73.0 \mu\text{g m}^{-3}$  at Gulou and Pukou, respectively. For PM<sub>2.1</sub>, the annual mean concentrations at the two sites were  $55.1 \pm 36.3 \mu\text{g m}^{-3}$  and  $64.8 \pm 40.2 \mu\text{g m}^{-3}$ . The concentration was at the same level as that of other cities in China except for mega cities, such as Beijing and Shanghai, but was much higher than that in the USA, Europe and Korea.

The size-fractionated PM at Gulou was mainly distributed from 10–5.8  $\mu\text{m}$  and 2.1–0.65  $\mu\text{m}$ , occupying 58.4% of the total concentration of PM<sub>10</sub>. At Pukou, the size-fractionated particles were mainly distributed from 2.1–0.65  $\mu\text{m}$ , 9.0–5.8  $\mu\text{m}$ , and below 0.43  $\mu\text{m}$ , which occupied 51.8% of the total concentration of PM<sub>10</sub>. The chemical compositions that constituted a large proportion of PM<sub>10</sub> were SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, Ca, NH<sub>4</sub><sup>+</sup>, Cl<sup>-</sup>, Fe, Al, K, and Mg. The concentrations of SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, and Ca at Gulou were significantly higher than those at Pukou. The chemical compositions that constituted a large proportion of PM<sub>2.1</sub> were SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, Cl<sup>-</sup>, K, Fe, Ca, Zn, Na, and Al.

The contributions of sources as conducted by the CMB model showed that at Gulou, the major sources of PM<sub>10</sub> were construction dust (29.62%), sulfate (16.80%), and nitrate (15.35%), while those of PM<sub>2.1</sub> were sulfate (30.71%), nitrate (28.05%) and coal combustion dust (15.87%). At Pukou, the three largest sources in PM<sub>10</sub> were construction dust (22.89%), coal combustion dust (21.57%) and sulfate (15.35%), while those in PM<sub>2.1</sub> were coal combustion dust (39.46%), sulfate (26.84%) and nitrate (17.39%).

The results in this paper will be beneficial for local management to create an efficient control policy to reduce airborne particles. Limiting the emissions of construction dust and coal combustion dust is necessary. The government should attach great importance to the harm of secondary aerosol and strengthen the control of industrial and vehicle exhaust emissions.

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