Elemental compositions of PM$_{2.5}$ and TSP in Lijiang, southeastern edge of Tibetan Plateau during pre-monsoon period

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ABSTRACT

PM$_{2.5}$ and total suspended particulate (TSP) samples were collected at Lijiang, southeastern Tibetan Plateau, China. Sixteen elements (Al, Si, S, K, Ca, Cr, Mn, Ti, Fe, Ni, Zn, As, Br, Sb, Pb and Cu) were analyzed to investigate their elemental compositions during the pre-monsoon period. The results showed that Ca was the most abundant element in both PM$_{2.5}$ and TSP samples. The enrichment factors (EFs) of Si, Ti, Ca, Fe, K and Mn were all below 10 for both PM$_{2.5}$ and TSP, and these elements also had lower PM$_{2.5}$/TSP ratios (0.32–0.34), suggesting that they were mainly derived from crustal sources. Elements Cu, Zn, S, Br and Sb showed strong enrichment in PM$_{2.5}$ and TSP samples, with their PM$_{2.5}$/TSP ratios ranging from 0.66 to 0.97, indicating that they were enriched in the fine fractions and influenced by anthropogenic sources. Analysis of the wind field at 500 hPa and calculations of back trajectories indicated that Al, Si, Ca, Ti, Cr, Mn and Fe can be influenced by transport from northwestern China during the dust-storm season, and that S, K, Ni, Br and Pb reached high concentrations during westerly transport from south Asia. Combined with the principle component analysis and correlation analysis, elements of PM$_{2.5}$ samples were mainly from crustal sources, biomass burning emissions and regional traffic-related sources.

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1. Introduction

The Tibetan Plateau is the Earth's highest plateau, and exerts profound thermal and dynamic influences on local and global climate as well as on atmospheric circulation of the Asian Monsoon System (Chan, Wong, Li, Chan, & Zheng, 2006). Because it is located far from any industrialized area and is lightly populated, the plateau has been chosen as an ideal location to observe the atmospheric environment and to evaluate various impacts of human activities (Cong, Kang, Liu, & Wang, 2007; Kang et al., 2002). To date, several aerosol particle studies have been conducted over the Tibetan Plateau, for example at Wudaoliang and Waliguan located northeast of the plateau (Liu, Zhang, & Shen, 1997; Wen, Xu, Tang, Zhang, & Zhao, 2001; Zhang, Arimoto, Cao, An, & Wang, 2001); on Muztagh Ata Mountain located in the northwest of the plateau (Cao et al., 2009; Wu, Xu, Zhang, Gao, & Yao, 2009); in the Himalaya located in the south of the plateau (Cong, Kang, Dong, Liu, & Qin,

2010; Li, Kang, & Cong, 2007; Shrestha, Wake, & Dibb, 1997); on Mt. Gongga and Mt. Yulong located in the southeast of the plateau (Yang et al., 2009; Zhang, He, Cao, Ho, & Shen, 2012; Zhang, He, Theakstone, & Pang, 2010); and at Nam Co located in the center of the Plateau (Cong et al., 2007). These studies have mainly focused on aerosol chemistry at remote sites over the plateau, and have given less attention to the transitional region at the plateau margin, in particular for the suburban environment near the city.

Lijiang city is located on the southeastern edge of the Tibetan Plateau, southwestern China, and is adjacent to south Asia and southeast Asia. Previous studies have found that pollutants related to human activities and biomass burning emissions from south Asia and southeast Asia not only influence the local atmospheric environment, but can also influence southwestern China by long-range transport (Chan et al., 2006; Engling et al., 2011; Zheng et al., 2007). Lijiang is a famous city for tourism. Increasing numbers of tourists are visiting the city, consequently influencing the environment, e.g., its water resources (Ning & He, 2007) and precipitation chemistry (Zhang et al., 2012). However, there have been no studies on the elemental composition of aerosol in the rural regions of Lijiang, particularly in terms of PM$_{2.5}$. The purpose of the present study is: (1) to investigate the elemental composition of

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TSP and PM$_{2.5}$ samples and (2) to determine the possible sources of elements in the atmosphere during the pre-monsoon period.

2. Methods

2.1. Site description

Lijiang city is located on the southeastern Tibetan Plateau, northwestern Yunnan Province, China (Fig. 1). Because of the attraction of the Old Town, Lijiang was listed as a World Heritage site in 1997. It is also a historic and cultural city of great value and importance (UNESCO World Heritage Centre 1997), and has gradually developed as a tourist center. In 2008, there were approximately 150,000 permanent residents in Lijiang city and over 6 million visiting tourists. In order to encourage tourism, heavy industry development has been limited in Lijiang district; however, the number of vehicles has grown rapidly in association with tourism development. Statistics indicate that the total number of vehicles increased from 9000 in 1995 to 87,000 in 2008 (Lijiang Statistics Yearbook), and vehicle exhausts have been regarded as the major local pollution source.

2.2. Meteorology

The climate of the Lijiang region is controlled by the Asian southwestern monsoonal circulation from May to October, and by the southern branch of the westerly circulation from November to April of the following year. During our sampling period, the prevailing circulation in the study area was dominated by the southern branch of westerlies and the plateau winter monsoon (Fig. 1).

Meteorological parameters including air temperature, air pressure, relative humidity, wind speed and wind direction were measured simultaneously during the sampling period (Table 1). There was very little precipitation during our sampling period (see Fig. 2), which could decrease the elemental mass concentration by wet scavenging effects, especially in TSP samples. Using the U,
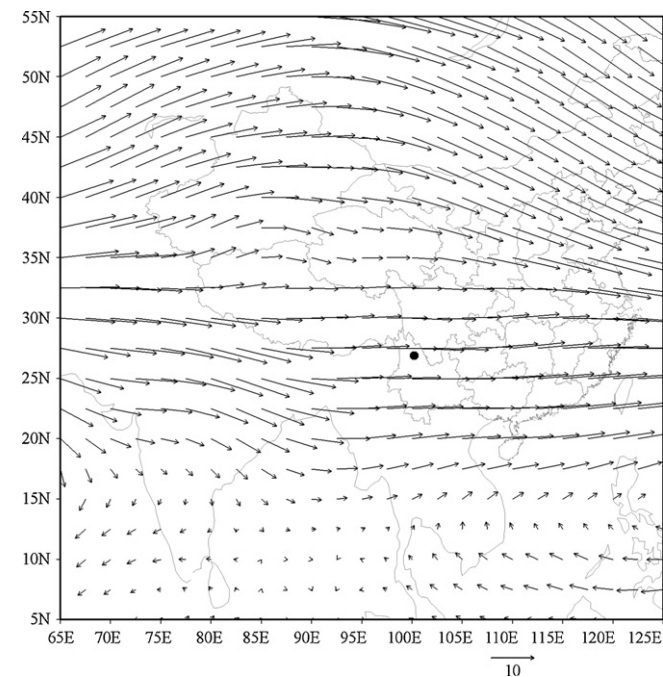
Table 1
Statistic meteorological status during sampling period.

Parameters	Mean	Max.	Min.
Temperature (°C)	15.7	20.7	8.7
Pressure (hPa)	762.2	767.3	757.9
Humidity (%)	44.7	81	29
Wind speed (m/s)	3.9	7.6	1.6

V-wind data downloaded from http://www.esrl.noaa.gov/psd/data/, the wind field at 500 hPa was plotted by Grads (Version 1.8) in Fig. 1.

2.3. Sampling and analysis

The sampling site was set about 5 m above the ground and 1.5 m above the roof of the Mt. Yulong Glacier and Environmental Monitoring Station building. There are some residential but no industrial emissions around the building, represented as a rural environment. PM$_{2.5}$ and TSP sampling was carried out during the pre-monsoon period (21 March to 16 May, 2009), once every two days, respectively. The collector (Zambelli Easy Plus 1, Zambelli srl, Milan, Italy) was driven by 220 V alternating current. Teflon® Zefluor™ filters (47 mm in diameter) with 2 μm pore size (Pall Corporation, Port Washington, NY) were used for sampling. The volume of air sampled was measured by an in-line flow meter with a mean flow rate of 16.7 L/min. Meanwhile, ambient temperature and pressure were converted to the standard (101,325 Pa, 273 K) cubic meters. Totally, 25 PM$_{2.5}$ and 24 TSP samples were collected for analysis. The filter cartridges were packed in clean plastic bags and transported in airtight containers. After sampling, the filters were removed from the cartridges and placed in pre-cleaned air-tight methacrylate bottles. Samples and seven blank filters were taken with care to minimize contamination both in the field and in the laboratory before analysis in the Institute of Earth Environment, Chinese Academy of Sciences (Xi'an).

The concentrations of elements in PM$_{2.5}$ and TSP samples were determined by energy dispersive X-Ray fluorescence (ED-XRF) spectrometry using the PANalytical Epsilon 5 XRF analyzer (PANalytical B.V., Almelo, The Netherlands), which uses three-dimensional polarizing geometry with 11 secondary targets (CeO$_2$, CsI, Ag, Mo, Zr, KBr, Ge, Zn, Fe, Ti, and Al) and one Barkla target (Al$_2$O$_3$) that supplies a good signal-to-background ratio, permitting the low detection limits. The X-ray source is a side window X-ray tube with a gadolinium (Gd) anode, which is operated at an accelerating voltage of 25–100 kV and a current of 0.5–24 mA (maximum power: 600 W). Characteristic X-radiation is detected by a germanium (Ge) detector (PAN 32). Each sample was irradiated for half an hour and a laboratory blank Teflon filter sample was also analyzed to evaluate analytical bias. The elements that were determined by the ED-XRF method include Al, Si, S, K, Ca, Cr, Mn, Ti, Fe, Ni, Zn, As, Br, Sb, Pb, and Cu with detection limits (μg/cm^2) of 0.115, 0.093, 0.032, 0.007, 0.007, 0.003, 0.014, 0.005, 0.011, 0.003, 0.008, 0.000, 0.006, 0.033, 0.015 and 0.010, respectively. Quality assurance/quality control (QA/QC) procedures were described in Xu et al. (2012).

3. Results and discussion

3.1. Elemental composition

Fig. 2 shows the temporal variations of all detected elemental mass concentrations in PM$_{2.5}$ and TSP, while statistical results for the element concentrations of PM$_{2.5}$ and TSP during the pre-monsoon period in 2009 are shown in Table 2. The PM$_{2.5}$/TSP ratio

Fig. 1. Location of Lijiang city (black dot) and average wind field of 500 hPa during sampling period.
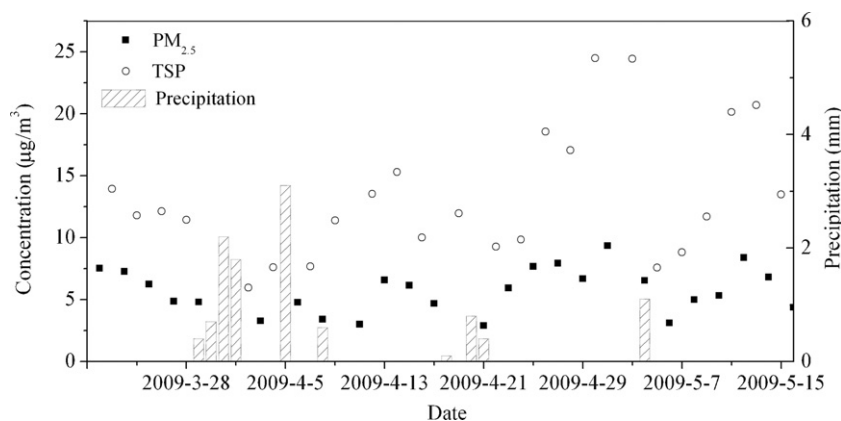
Fig. 2. Temporal variation of precipitation and detected elemental mass concentration in PM$_{2.5}$ and TSP.

of each element and the elemental concentrations of aerosols from other sites are also listed for comparison in Table 2. In general, PM$_{2.5}$ elemental mass concentrations decreased in the order Ca, S, Al, Fe, Si, Ti, Zn, Sr, Mn, Pb and Sb, with the remaining elements being lower than 10 ng/m^3. Similarly, the decreasing order of mass concentration in TSP was Ca, Al, Fe, S, Si, Ti, Zn, Pb and Sb. It was noticed that the concentration of Ca was greatest in both TSP and PM$_{2.5}$ since the soil/road dust was rich in calcium carbonate at Lijiang. Elements such as Ca, Si, Al and Fe, whose mass concentrations exceed 1 μg/m^3, were the major elements in TSP, together contributing 79% of the total detected elemental mass. These same elements occupied 62% of the total detected elemental mass concentration in PM$_{2.5}$ samples. These results indicate that our samples were mainly derived from crustal sources. Moreover, PM$_{2.5}$/TSP ratios of Ca, Al, Si, and Fe were 0.35, 0.38, 0.35 and 0.36, respectively, suggesting that those elements were predominantly rich in TSP. Similar results were also found for Ti, Mn and Cr which had PM$_{2.5}$/TSP ratios of 0.36, 0.37 and 0.48, respectively. Otherwise, PM$_{2.5}$/TSP ratios of S, Ni, Br, Sb and Cu were higher than 0.5, indicating that they were predominant in fine particles.

For PM$_{2.5}$, it was not only found that the crustal elements except Ca were all lower in our samples, but also that anthropogenic elements such as Pb, Zn and Cu were one magnitude lower than those

in Beijing (He et al., 2001) and Chengdu (Wang et al., 2010). Meanwhile, the mass concentrations of Zn, Ni and Pb, which are related to human activities, were also lower than those in PM$_{2.5}$ samples collected at Mt. Gongga (101°59′E, 29°35′N, 1600 m a.s.l.) on the southeastern edge of the Tibetan Plateau (Yang et al., 2009), which is far from any industrialized areas. This comparison indicates that there were slight anthropogenic pollutants emissions in Lijiang under the developing tourism. Despite this, anthropogenic influences were still noted in atmospheric TSP samples due to urban expansion and increasing tourism, and most of the elemental mass concentrations in our TSP samples, particularly those of crustal elements, were greater than those in samples collected in a rural area of Lijiang during winter 2003 (Zhang, Zou, Shen, & Wang, 2007).

3.2. EFs and PM$_{2.5}$/TSP ratios

Crustal enrichment factors (EFs) and size-fractionated concentration data of aerosol elements and species provide clues regarding the sources and/or source processes of the elements and species. Particulate species that result from gas-to-particle conversion processes and elements that are emitted during combustion and other high-temperature processes tend to be mainly associated with the fine aerosol particles, whereas aerosol components that

Table 2
Statistical summary of elemental and ionic concentrations (ng/m^3) determined at Mt. Yulong and comparison with data over Tibetan Plateau.

	PM$_{2.5}$				TSP				PM$_{2.5}$/TSP	Mt. Gongga[a] (PM$_{2.5}$)	Chengdu[b] (PM$_{2.5}$)	Beijing[c] (PM$_{2.5}$)	Lijiang[d] (TSP)
	Average	SD	Max.	Min.	Average	SD	Max.	Min.					
Al	619.01	269.26	1124.02	202.83	1719.63	897.83	3541.41	634.69	0.36	295.80	1582.00	800.00	223.90
Si	377.53	176.60	759.85	54.38	1130.46	742.24	2762.54	314.56	0.33		1185.00	2390.00	619.00
S	1139.07	562.20	2770.82	430.73	1184.73	671.29	2869.02	277.48	0.96		2597.40	6570.00	71.70
K	595.11	263.87	1262.23	292.87	970.95	508.96	2306.24	377.50	0.61		2802.10	2830.00	73.20
Ca	1684.44	527.07	2874.27	884.88	5210.25	1632.74	8431.55	2229.49	0.32	372.80	1306.90	1230.00	580.10
Ti	55.24	22.33	96.45	22.71	165.43	78.88	366.30	56.69	0.33		121.60		18.10
Cr	1.92	1.72	5.36	0.00	4.76	2.58	11.81	1.84	0.40		7.20		3.00
Mn	14.73	8.42	33.33	0.00	39.57	25.54	117.29	5.07	0.37		74.80	97.00	9.50
Fe	510.09	211.14	854.05	197.66	1483.99	721.88	3209.46	592.75	0.34	224.00	1425.90	1140.00	83.60
Ni	1.74	2.09	6.77	0.00	2.79	1.78	5.65	0.00	0.62	0.90	3.30	15.00	2.90
Zn	39.60	20.82	115.39	16.56	59.74	32.25	141.35	25.11	0.66	154.60	323.90	480.00	13.20
As	0.72	0.82	2.42	0.00	2.01	3.61	17.44	0.00	0.36	4.30	0.40		6.20
Br	5.91	5.38	18.33	0.00	6.10	4.91	19.17	0.00	0.97		9.00	17.00	10.10
Sb	11.67	11.48	50.23	0.00	14.34	19.95	98.95	0.00	0.81				
Pb	14.21	10.63	38.01	0.00	46.27	108.06	516.06	2.83	0.31	39.40	132.90	304.00	17.70
Cu	8.56	8.89	36.66	0.00	10.11	6.38	29.97	2.95	0.85	2.20	23.80	35.00	5.10

[a] Yang et al. (2009).
[b] Wang et al. (2010).
[c] He et al. (2001).
[d] Zhang et al. (2007).

are generated by low-temperature dispersion processes, such as sea salt and soil erosion, have most of their mass in the coarse size fraction (Mkoma, Maenhaut, Chi, Wang, & Raes, 2009). The EFs of elements in aerosols relative to the crustal material are often used to differentiate between elements originating from crustal material and those from anthropogenic sources (Al-Momani et al., 2005; Han, Cao, Jin, & An, 2009; Ragosta, Caggiano, Macchiato, Sabia, & Trippetta, 2008). The EF is generally defined as follows:

$$EF_X = \frac{(C_X/C_R)_{aerosol}}{(C_X/C_R)_{crust}},$$

where X represents the elements of interest; EF_X is the EF of X; C_X is the concentration of X; C_R is the concentration of a reference element; and the aerosol and crust subscripts refer to particles in the aerosol samples and crustal material, respectively. It is widely accepted that an EF close to unity indicates a dominant crustal source for that element, while an EF greater than 10 points to a predominantly anthropogenic source. The reference elements commonly used are Al, Si, Ti, Fe, etc. In this study, Al was selected as the reference material, and Wedepohl's (1995) average upper continental crust composition was adopted as the elemental composition of the crust material.

In decreasing order of $PM_{2.5}$ elements, the EFs of 15 elements (except Al) in $PM_{2.5}$ and TSP collected at Lijiang city are shown in Fig. 3. According to their elemental $PM_{2.5}$/TSP ratios, the elements could be divided into three main groups, as follows.

(i) Elements such as Si, Ti, Ca, Fe, K and Mn with EFs below 10 in both $PM_{2.5}$ and TSP, which also had low $PM_{2.5}$/TSP ratios (0.32–0.34), suggesting that these elements were mainly dominant in the coarse fraction and were derived from crustal sources.

(ii) Elements such as Cu, Zn, S, Br and Sb showed strong enrichment in $PM_{2.5}$ (>106) and TSP (>41); in particular the EF value for Sb was 6302 in $PM_{2.5}$ and 4001 in TSP. Previous studies have considered that these enriched elements originated from various anthropogenic sources, in particular those related to traffic (Almeida-silva, Canda, Freitas, Dung, & Dionísio, 2011; Chueinta, Hopke, & Paatero, 2000; Lee, Garland, & Fox, 1994; Nriagu & Pacyna, 1988; Rogge, Hildemann, Mazurek, Cass, & Simoneit, 1993). For example, Cu is predominantly from brake
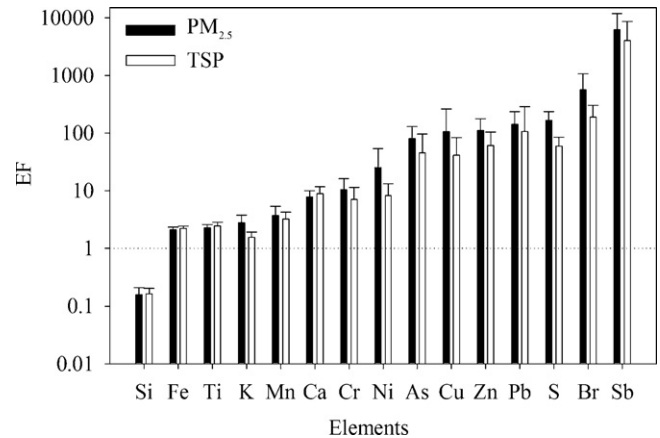

Fig. 3. EFs of detected elements in TSP and $PM_{2.5}$ samples.

dust and fossil fuel combustion, while fossil fuel combustion is also enriched in Zn, S, Br and Sb. As the most highly enriched element in our samples, Sb was also found to be enriched in TSP from Saclay (near Paris) (Ayrault, Senhou, Moskura, & Gaudry, 2010), and in $PM_{2.5}$ in a traffic tunnel in Lisbon (Almeida-silva et al., 2011). Almeida-silva et al. (2011) noted that Sb was mainly from brake wear, while Weckwerth (2001) attributed Sb to be mainly from diesel-soot in the fine fraction and from abraded tyre material and brake linings in the coarse fraction. The $PM_{2.5}$/TSP ratios of those elements in this group ranged from 0.66 to 0.97, suggesting that they were predominantly composed of fine fractions, consistent with the evidence that elements mainly associated with the fine aerosol particles were emitted during combustion and other high-temperature processes.

(iii) In this group, it is interesting that although As and Pb were enriched both in $PM_{2.5}$ and TSP samples, the $PM_{2.5}$/TSP ratios of As and Pb were 0.36 and 0.31, respectively. This indicates that the main contribution to enrichment of As and Pb in the aerosol was by the coarse size fraction. Sources of As in the environment can be natural, anthropogenic, or both (Fang, Lin, Huang, & Huang, 2011; Roy & Saha, 2002). Research on the environmental background values of soils in Xizang, China, indicated that the concentration of As and Pb in the soil was higher than
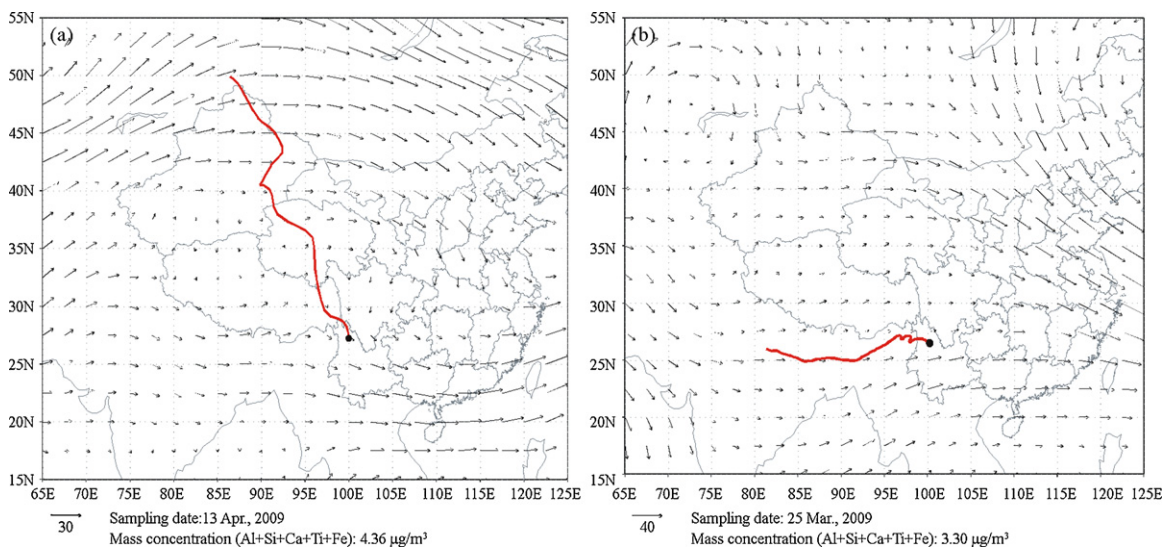

Fig. 4. Typical backward trajectory (red line) and wind field of 500 hPa for (a) northerly transport and (b) westerly transport. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the average level for the rest of China (Zhang, 1994). Moreover, it was also found that As was enriched in topsoil from the western Tibetan Plateau (Li, Kang, & Zhang, 2009), and that As and Pb were enriched in aerosol from the southeastern Tibetan Plateau (Yang et al., 2009; Zhang, Cao, Ho, & He, 2011). Therefore, the high enrichments of As and Pb may reflect that As and Pb have a high background value on the Tibetan Plateau. In addition, soil/road dust re-suspension may also contribute to the high EFs and low $PM_{2.5}$/TSP ratios of As and Pb.

3.3. Identification of $PM_{2.5}$ element sources

Using NCEP (National Centre for Environmental Prediction) reanalysis data (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html), wind fields at 500 hPa over the sampling site were established for each sampling day. At the same time, back trajectories for 6 days were calculated for the sampling site (www.arl.noaa.gov/ready/hysplit4.html). Meteorological data fields to calculate the trajectories were available from GDAS (global data assimilation system), and each trajectory was started at 04 UTC at an altitude of 1000 m above ground level (AGL). By combining the wind field with back trajectories for each sample, the main transport was classified into three groups: one dominated by westerly transport from south Asia and northern Myanmar directly (8 samples); another was transported throughout the Tibetan Plateau and northern Myanmar (15 samples) by the plateau winter monsoon; and the last by northerly transport from northwestern China along the eastern edge of the Tibetan Plateau (2 samples). The relationship between elemental concentration and transport type is complex. In particular, transport from throughout the plateau originated from south Asia or central Asia, and then passed over the plateau, increasing the difficulty of elemental source identification. Therefore, we have focused only on the long-range transport from westerly and northerly directions (Fig. 4), and calculated the W/N (westerly transport/northerly transport) ratio.

The W/N ratios of elements in $PM_{2.5}$ samples shown in Fig. 5 indicate that the W/N ratios of crustal elements such as Al, Si, Ca, Ti, Cr, Mn and Fe are lower than unity, suggesting that the concentrations of those elements during northerly transport are greater than those during westerly transport. We note that the sampling period coincided with the dust-storm season in northwestern China, and that high concentrations of dust aerosol can be transported over the whole of East Asia, even to the Pacific and North America (Shen et al., 2007, 2011; Stone, Yoon, & Schauer,
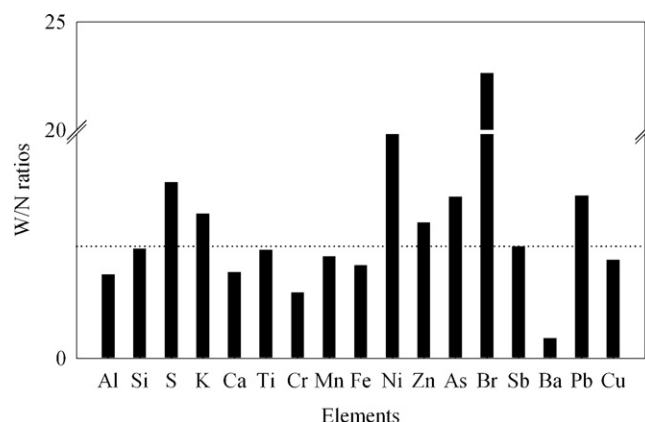

Fig. 5. The W/N ratios of detected elements.

2011; Sullivan, Guazzotti, Sodeman, & Prather, 2007; Zhang, Shen, Cheng, Zhang, & Liu, 2010). Thus, the crustal elements can be transported to our site by long-range transport under favorable atmospheric circulation patterns (Fig. 4(a)). On the other hand, the W/N ratios of S, K, Ni, Br and Pb were greater than unity, indicating that these elements had a higher concentration during westerly transport (Fig. 4(b)). This was most notably seen in Br, which had the highest W/N ratio (22.64) as shown in Fig. 5. Previous studies have reported that Br has various sources, including marine aerosols, leaded gasoline combustion, biomass burning, and coal combustion (Gao et al., 2010). A large number of forest fires sites were burning in northern Myanmar and eastern India during our study period (http://firefly.geog.umd.edu/firemap/). These emissions from forest fires can be transported to our site by the westerly circulation, causing the higher W/N ratios of Br, S and K. Meanwhile, the concentrations of Ni, Zn, As and Pb were also greater during westerly transport than those during northerly transport, which may be related to anthropogenic emissions from south Asia. Overall, northerly transport brought mostly crustal elements, while elements related to biomass burning and human activities were mainly contributed by westerly transport.

3.4. Principal component analysis and correlation analysis

Principal component analysis (PCA) with varimax rotation was used to determine the various sources of elements in the $PM_{2.5}$ samples (Han et al., 2009; Kothai, Saradhi, Pandit, Markwitz, &

Table 3
Rotated component matrix for $PM_{2.5}$ elements at Lijiang during pre-monsoon period.

Elements	Principal components					Extraction
	1	2	3	4	5	
Al	**0.937**	0.194	0.000	0.180	0.073	0.953
Si	**0.759**	0.463	−0.082	0.122	−0.031	0.813
S	0.282	**0.897**	0.239	0.019	−0.092	0.950
K	0.545	**0.745**	0.145	0.042	−0.092	0.884
Ca	**0.901**	−0.184	0.058	−0.099	0.152	0.883
Ti	**0.884**	0.389	0.005	0.114	0.012	0.945
Mn	**0.587**	0.481	0.225	0.131	−0.441	0.838
Fe	**0.894**	0.345	−0.019	0.185	−0.043	0.955
Ni	0.063	0.252	**0.844**	−0.121	−0.114	0.807
Zn	0.081	0.431	**0.660**	0.502	−0.026	0.881
Br	0.093	**0.602**	0.441	0.176	0.389	0.748
Pb	0.231	0.041	0.093	**0.910**	−0.237	0.947
Cu	−0.092	0.006	**0.931**	0.149	0.017	0.897
Sb	0.116	−0.027	−0.055	−0.211	**0.902**	0.876
% of variance	33.302	19.723	16.858	9.397	9.134	
Cumulative %	33.302	53.025	69.883	79.280	88.414	

PCA loading > 0.5 are shown in bold. Factor loadings > 0.7 are excellent (Han et al., 2009).

Puranik, 2011). Because of low extraction ratios (<0.6), As and Cr were excluded from the PCA. At the same time, correlation coefficients between elements were calculated. Table 3 shows the principal component patterns for individual samples. Five principal factors were obtained, accounting for 88.41% of the total variance. The first factor, accounting for 33.30% of total variance, was dominated by Al, Si, Ca, Ti and Fe, with a lesser contribution from Mn. The correlations between elements in this group were significant (Si, Ca, Ti, Fe and Mn correlated with Al with coefficients of 0.87, 0.78, 0.91, 0.96 and 0.69, respectively; $P < 0.01$). These results suggest that this factor was attributed to soil dust. The second component had high loadings from S, K and Br, accounting for 19.72% of total variance. The correlation coefficients between S and K, S and Br and K and Br were 0.88 ($P < 0.01$), 0.62 ($P < 0.01$) and 0.49 ($P < 0.05$), respectively. As noted above, this group was considered to represent the influence of biomass burning via long distance transport from south Asia and northern Myanmar. The third group was characterized by Ni, Zn and Cu, reflecting the contribution from traffic-related sources in the local region as well as in parts of south Asia via long-range transport. Correlation coefficients between Ni and Zn, Ni and Cu and Zn and Cu were 0.69 ($P < 0.01$), 0.73 ($P < 0.01$) and 0.75 ($P < 0.01$), respectively. This component explained 16.86% of the total data variance. The last two components were mainly loaded by Pb and Sb, accounting for 9.40% and 9.13% of total variance, respectively, and they did not show significant correlation with the other elements. This pattern of Pb, Sb, As and Cr occurrence may indicate that those elements were not from a single source but instead had multiple sources. As mentioned above, As and Pb were mainly derived from crustal sources, but can also be influenced by traffic combustion. Meanwhile, Cr is commonly considered as being soil/dust-derived; however, Echalar, Gaudichet, Cachier, and Artaxo (1995) pointed out that Cr can be enriched in forest fires. Sb can be sourced directly from traffic-related emissions and indirectly from re-suspended or dispersed road dust.

4. Conclusions

(1) Ca, Si, Al and Fe were the major elements in both PM$_{2.5}$ and TSP samples, together contributing 62% and 79% of the total detected elemental mass, respectively.
(2) EFs of Al, Si, Ti, Ca, Fe, K and Mn were below 10 both in PM$_{2.5}$ and TSP, and the PM$_{2.5}$/TSP ratios of all these elements were below 0.5; Cu, Zn, S, Br and Sb showed strong enrichment in PM$_{2.5}$ (>106) and TSP (>41), and their PM$_{2.5}$/TSP ratios were all greater than 0.5.
(3) According to backward trajectory and wind field analyses, Al, Si, Ca, Ti, Cr, Mn and Fe can be transported from northern China and are related to dust-storms. Meanwhile, Br, S, K, Ni, Zn, As and Pb had higher concentrations during westerly transport.
(4) By calculating the principal components and correlation coefficients, it was found that Al, Si, Ca, Ti, Fe and Mn were derived from crustal material; S, K and Br were associated with biomass burning in south Asia and northern Myanmar; Sb, Ni, Zn and Cu were mainly accounted for by regional traffic-related process emissions; and As, Cr and Pb had complex sources.

As a whole, the chemical composition of aerosol is influenced by various sources at Lijiang region, and more pollutants related to biomass burning and anthropogenic activities should be transported to southwest China from south Asia during the southwest monsoon period. Thereby, the chemical composition (including ionic, elemental and carbonaceous composition) of different particle sizes aerosol samples will be carried out during monsoon and non-monsoon period in further studies.

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