Analysis of the transport pathways and potential sources of PM$_{10}$ in Shanghai based on three methods

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**A B S T R A C T**

In this study, we investigated the transport pathways and potential sources of PM$_{10}$ in Shanghai based on PM$_{10}$ monitoring data recorded from 2006 to 2009 using three methods: backward trajectory cluster analysis, trajectory sector analysis (TSA) and potential source contribution function (PSCF). Seven clusters were generated from the backward trajectory cluster, and two potential sources were identified from the PSCF method. Among the seven clusters, three northerly clusters corresponded to the winter monsoon. The northerly air flow transported high-concentration PM$_{10}$ that had been emitted from northwestern sources, including Hebei, Shandong, Anhui and Jiangsu to Shanghai in winter and spring. The other three southerly clusters were associated with the summer monsoon caused by the Indian low and the Subtropical high over the western Pacific Ocean controlling the weather patterns of the eastern coastal area in summer. Corresponding to the southerly path, the PSCF method also identified a southwestern source including Zhejiang, Jiangxi and Fujian. The remaining eastern cluster, which represented the transition of monsoons, did not contribute much to the PM$_{10}$ concentration in Shanghai. According to the results of TSA, the relative PM$_{10}$ contribution to Shanghai of the northwestern source was approximately twice that of the southwestern source.

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1. Introduction

Atmospheric particulate matter (PM) is emitted into the atmosphere from natural and anthropogenic sources. PM can affect climate change, visibility distribution (Chang et al., 2009; Huang et al., 2009), biogeochemical cycles and atmospheric chemistry (Lian et al., 2009; Zhang et al., 2009b) as well as adversely affect public health (Brunekreef and Forberg, 2005; Cai et al., 2008; Chen et al., 2004; Huang et al., 2009; Kan et al., 2007; Li et al., 2004; Waheed et al., 2010; Yue et al., 2006). PM could also make a significant impact on atmospheric properties during its global transport course (Yang et al., 2005). Therefore, PM pollution is a significant problem worldwide especially in less-industrialized countries (Yue et al., 2006).

As the largest developing country in the world, China has achieved rapid development in the recent two decades. However, rapid economic growth, urbanization, population growth and industrialization have significantly damaged the air quality (Waheed et al., 2010; Zhang et al., 2009b). Indeed, air pollution levels in China are among the highest in the world (Chen et al., 2004).

The Yangtze River Delta (YRD), with an area of 210,700 km$^2$ and a population of 147 million, is an important economic region in China. Shanghai is located at the east of the Yangtze River Delta Region (31.23°N, 121.48°E) and faces the East China Sea (see Fig. 1a).

Shanghai is the largest city in the YRD region with an area of 6340.5 km$^2$ which covers 17 districts and a county, and a population of 14 million (Shanghai Year Book, 2010). It is the economic center of eastern China, and its industrial structure includes heavy industries, financial industries and other service industries (Shanghai Statistical Yearbook, 2010). In the past two decades, Shanghai has undergone rapid economic development.

With rapid economic development and industrialization, the air quality in Shanghai has deteriorated during recent years (Chen et al., 2004; Feng et al., 2009). For example, high PM concentrations and poor visibility are common (Streets et al., 2008; Tie et al., 2008). The Shanghai Environmental Bulletin announced that inhalable airborne particle (PM$_{10}$, or, particulate matter with aerodynamic diameter less than 10 μm) was the primary air pollutant in Shanghai. The annual average PM$_{10}$ concentration in urban areas from 2006 to 2009 were 86 μg/m$^3$, 88 μg/m$^3$, 84 μg/m$^3$ and 81 μg/m$^3$, respectively (Shanghai Environmental Bulletin, 2006–2009). Each of these values fell below the annual average limit of the second-class standard for PM$_{10}$ (100 μg/m$^3$) as defined in ‘Ambient Air Quality Standard of China’ (GB3095-1996) but exceeded the guideline of 20 μg/m$^3$ recommended by the World Health Organization (WHO, 2006). Additionally, PM$_{10}$ was identified as the primary pollutant in 321, 328, 328 and 344 days yearly from 2006 to 2009, respectively, corresponding to 87.9%, 89.9%, 89.6% and 94.2% of the total days of the year (Shanghai Environmental Bulletin, 2006–2009).

The characteristics of aerosols were widely studied in Shanghai, including seasonal variations (Ye et al., 2003), compositions (Ye et
al., 2003), size distributions and existing forms of major ions (Xiu et al., 2004). In addition to local pollution, Shanghai may also be affected by the long-range and mesoscale transport of large anthropogenic emissions from East Asia under the influence of the monsoon system, especially during winter. In winter and spring, sand storms from the northwest of China may further deteriorate the ambient air quality (Fu et al., 2010; Oanh and Pongkiatkul, 2007; Wang et al., 2006). Intensive knowledge of the transport pathways and potential sources of PM$_{10}$ were required to effectively control PM$_{10}$ pollution in Shanghai (Yang et al., 2005).

2. Data and methods

2.1. Climatic features in Shanghai

Shanghai is characteristic of the subtropical monsoon climate, with a marked change of wind direction, temperature and rainfall in spring and autumn (Wang et al., 2006).

2.1.1. Wind

2.1.1.1. Wind direction. Fig. 2 shows the wind roses of typical months in four seasons. In winter (December, January and February), the prevailing wind is northerly, with an average monthly frequency of 54%. In summer (June, July and August), the prevailing wind is southerly, with an average monthly frequency of 53% (Chan and Yao, 2008). Spring and autumn are transitional seasons of wind directions, and eastern to southeastern wind prevails in spring, while eastern to northeastern wind prevails in autumn (Su, 1997).

Some studies have reported that air parcels arriving in Shanghai during summer primarily came from the East China Sea and carried clean air. In contrast, air parcels arriving in Shanghai in winter came from northeastern (Yellow Sea) to northwestern (inland) directions and carried polluted air from Jiangsu province (Feng et al., 2006). Influenced by the distinction of thermal conditions between land and water, when there is no strong weather system affecting Shanghai, a clear diurnal variation of wind direction can be observed (Su, 1997).

2.1.1.2. Wind speed. In Shanghai, the average monthly wind speed peaks in March and April at approximately 4–4.4 m/s, and the minimum average wind speed occurs in October and November, with winds at approximately 2.7 m/s, on average. In the remaining months, the average wind speed ranges from 3.4 to 3.9 m/s (Yan, 1996).

2.1.2. Precipitation

Annual precipitation in Shanghai ranges from 1027 to 1111 mm/yr with 70% occurring between April and September. The largest amount of precipitation is typically found in June and September (120–160 mm), while the lowest amount occurs in December and January (30–45 mm) (Yan, 1996; Su, 1997).

2.2. PM$_{10}$ data

PM$_{10}$ was monitored daily at 19 stations (Fig. 1b), nine of which were located in the urban area of Shanghai, including Huangpu, Luwan, Xuhui, Changning, Jingan, Putuo, Jiabei, Hongkou and Yangpu. Daily PM$_{10}$ Air Pollution Index (API) data were obtained from the Shanghai Environmental Monitoring Center (SEMC) website (SEMC, 2006–2009). Daily PM$_{10}$ data used in this study were derived from the PM$_{10}$ API values from nine urban stations from 2006 to 2009 (Wang et al., 2006). Fig. 3 shows the seasonal variation of PM$_{10}$ concentration. The highest PM$_{10}$ concentrations in Shanghai consistently occurred in winter, followed by spring, and then summer and autumn. In summer and autumn, the clean southeastern winds from the East China Sea and Pacific Ocean result in the dilution of air pollutants and carry the industrial pollutants emitted from the steel industry zone in the north of Shanghai out of the region. In winter and spring, the prevailing northerly continental air mass carries pollutants from inland and steel industry zones to the downwind zone of Shanghai. Therefore, the PM$_{10}$ concentrations observed in winter and spring are higher than those in summer and autumn (Waheed et al., 2010).
2.3. Backward trajectory modeling

A backward trajectory model represents the recent history of an air mass. An air mass trajectory can provide information about the source regions that impact a given site (Dutkiewicz et al., 2006).

The backward air mass trajectories were calculated using the HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory, Version4) model of the ARL (Air Resources Laboratory) of NOAA (National Oceanic and Atmospheric Administration). The model was driven by NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Global Reanalysis meteorological data. The input data were available 4 times each day (0, 6, 12, 18 UTC) on the surface and at 17 mandatory pressure levels ranging from 10 to 1000 hPa (Oanh and Pongkiatkul, 2007). The model computed air-mass locations at 1-h intervals.

Transport distances at the regional scale or mesoscale is always within 1 km for approximately 2 to 3 days at the boundary layer. Thus, we chose a backward trajectory length of 72 h, and each trajectory consisted of 72 data pairs of latitude and longitude. Four back trajectories were calculated with times ending at 02:00, 08:00, 14:00, 20:00 LST and at a height of 200 m above the starting point located at ground level. We selected 200 m as the receptor height for the following reasons. First, PM$_{10}$ concentrations are often measured below the surface layer, typically at 200 m, and pollutants below this layer are well mixed. Second, both horizontal and vertical advections were considered when calculating the backward trajectories. Thus, air masses from higher or lower heights could reach the 200 m receptor height (Bari et al., 2003; Zhu et al., 2011).

Backward trajectories began at the People’s Square, the center of Shanghai (31.23136°N, 121.47004°E). In total, 5820 trajectories were generated throughout the study period.
2.4. Trajectory cluster analysis method

Cluster analysis is a multivariate statistical technique which has increasing applications in air pollution research. This approach splits a data set into a number of groups that are as homogeneous and as distinctly different from each other as possible (Brankov et al., 1993). Cluster analysis accounts for variation in transport speed and direction simultaneously, yielding clusters of trajectories that have similar length and curvature.

In our study, we converted the latitude and longitude of hourly backward trajectory endpoints into x and y distances in Cartesian coordinate, respectively, which were later used as clustering variables (Bari et al., 2003; Cape et al., 2000; Sirois and Bottenheim, 1995). Afterwards, the PM$_{10}$ concentrations associated with the backward trajectories in each cluster were compared. In this study we used Euclidean distance (see Eq. (1)).

$$d_{ij} = \sqrt{\sum_{i=1}^{n} \left( (X_{1i}-X_{2i})^2 + (Y_{1i}-Y_{2i})^2 \right)}$$ (1)

where $X_{1i}$($Y_{1i}$) and $X_{2i}$($Y_{2i}$) respectively referred to the x and y coordinates of backward trajectories 1 and 2 (Sirois and Bottenheim, 1995).

A two-stage clustering method was used to produce clusters. In the first stage (the hierarchical clustering stage), the number of clusters was selected, and the mean trajectories of each cluster were defined, which were further used as seeds for the second stage (the k-means clustering stage). The goal of the k-means clustering is to divide the dataset into a specific number of homogeneous clusters (k). The cluster membership can be determined based on the distance between a given data point and the kth center (Beaver and Palazoglu, 2006; Oanh and Pongkiatkul, 2007).

2.5. TSA method

TSA is a statistical approach that is used with air trajectories to compute average concentrations from various directions to evaluate the effect of air masses from various directions on PM$_{10}$ concentrations. In this study, the trajectory directions calculated using HYSPLIT4 were defined by 12 sectors of 30° each, numbered clockwise, with sector 1 from due north and 30° east of north (see Fig. 4) (Dutkiewicz et al., 2000; Husain and Dutkiewicz, 1990; Parekh and Husain, 1982). Eqs. (2.1)–(2.3) were used to calculate the mean PM$_{10}$ concentration from sector j ($C_j$) and the relative contribution from sector j ($\%C_j$).

$$C_i = \frac{\sum_{j=1}^{n} C_{ij}}{N_j}$$ (2.1)

$$N_j = \sum_{i=1}^{n} f_{ij}$$ (2.2)

$$\%C_j = \frac{C_j N_j}{\sum_{j=1}^{n} C_j N_j} \times 100$$ (2.3)

where $N$ is the total number of trajectories, $C_j$ is the concentration of PM$_{10}$ within the ith trajectory, $f_{ij}$ is the time passed through sector j for the ith trajectory (the fraction of time spent in each of the j sectors), $C_{ij}$, and $N_j$ is the total time during which trajectories passed through sector j (Bari et al., 2003; Hazi et al., 2003; Husain and Dutkiewicz, 1990; Zhu et al., 2011).

Ideally, 6-h $C_j$ concentrations are preferred. However, using the 24-h mean PM$_{10}$ concentration calculated from daily PM$_{10}$ API for each of the four 6-h periods yields representative results, as trajectory directions do not widely vary during a 24-h period. We assumed that the four 6-hour trajectories contributed equally to the observed PM$_{10}$ concentrations (Husain and Dutkiewicz, 1990; Parekh and Husain, 1982).

2.6. PSCF method

PSCF is a receptor model that incorporates meteorological information in its analysis scheme to produce a probability field that can be used to determine source emission potential (Cheng et al., 1993). PSCF is a conditional probability function giving the probability that an air parcel with a certain level of pollutant concentration arrives at a receptor site after passing through a specific upwind source area (Hopke and Hwang, 2007; Hopke et al., 2007). The possible source region is divided into a gridded i by j array. Atmospheric removal and chemistry during transport are currently not treated in the model (Cheng et al., 1993).

The PSCF value for the ith cell is then defined as

$$\text{PSCF}_{ij} = \frac{m_{ij}}{n_j}$$ (3)

where $n_j$ is the number of trajectories that originate in the ith grid during the study period and $m_{ij}$ is the number of trajectories that arrived at a receptor site with pollutant concentrations higher than a specified criterion value (in our study, the 70th percentile of PM$_{10}$ concentrations was used as the criterion value) (Oanh and Pongkiatkul, 2007; Zeng and Hopke, 1989). It is important to note that a grid with no end points ($n_j=0$) cannot be identified as a source area in the analysis even though there are known emission sources in the grid cell (Cheng et al., 1993).

In the current study, the domain for PSCF computation stretched 76° in latitude and 76° in longitude, with the center of Shanghai (31.23136°N, 121.47004°E) as the midpoint, and contained 23,104 grid cells of $0.5^\circ \times 0.5^\circ$.

Source areas are indicated by high PSCF values (Biegalski and Hopke, 2004; Han et al., 2005; Hsu et al., 2003a; Hsu et al., 2003b; Zeng and Hopke, 1989). However, a region with a low value of PSCF does not necessarily indicate low emissions from the region because they may not be transported to the receptor site (Polissar et al., 2001).

When calculating PSCF values, some grid cells will contain only 1 endpoint ($n_j=1$). If this endpoint happens to correspond to a
pollution event trajectory, the PSCF for these cells will be 1, but the confidence in these PSCFs will be very low. To remove the large uncertainty, a weight function $W(n_{ij})$ is multiplied by the PSCF value to better reflect the uncertainty in the values for these cells (Cheng et al., 1993; Hopke and Hwang, 2007; Zeng and Hopke, 1989).

In our study the $W(n_{ij})$ was:

$$W(n_{ij}) = \begin{cases} 1.00 & (n_{ij} > 80) \\ 0.70 & (25 < n_{ij} = 80) \\ 0.42 & (15 < n_{ij} = 25) \\ 0.17 & (n_{ij} < 15) \end{cases}$$

(4)

The $W(n_{ij})$ values were based on previous research (Han et al., 2005; Oanh and Pongkiatkul, 2007; Polissar et al., 2001; Yli-Tuomi et al., 2003; Zhu et al., 2011). The classification of $n_{ij}$ was obtained empirically by running the PSCF Fortran program multiple times (Zhu et al., 2011).

3. Results and discussion

3.1. Clustering results

In the average-linkage clustering stage, no obvious jump point could be determined. We attempted to use four to nine clusters. After a visual inspection, it was determined that using seven clusters provided the best representation of air mass classifications. The numbers of trajectories found in the seven clusters were respectively 1540, 1046, 1114, 961, 696, 144 and 319. Fig. 4 illustrates the mean trajectories of each cluster, and Fig. 5 shows the trajectories within each cluster.

Fig. 6 shows the monthly frequencies of the seven clusters. We attempted to link the frequency distribution of the seven clusters with the monsoon climate of Shanghai.

The seasonal transition of prevailing wind direction is clear in Shanghai. During April to August, influenced by the summer monsoon, the prevailing wind direction is southeast to east (clusters #4, #6, #7). In November to February, influenced by the winter monsoon, northwesterly directions (inland) prevail in Shanghai (clusters #2, #3) (Yan, 1996).

Trajectories from various directions had distinct effects on the PM$_{10}$ concentrations (Fig. 7). The mean PM$_{10}$ concentrations for clusters #1–#7 were respectively 80.5, 91.7, 98.1, 91.5, 74.9, 70.8 and 70.3 $\mu$g/m$^3$. The highest PM$_{10}$ concentration was found in cluster #3, followed by cluster #2 and cluster #4. Cluster #2 and cluster #3 may represent the effect of continental air masses from the northwest of China in winter and spring, while cluster #4 may represent the effect of air masses from the southwestern PM$_{10}$ sources in summer (Fig. 4). The lowest PM$_{10}$ concentrations were found in cluster #7 and cluster #6, which represent the effect of clean marine air masses from the South China Sea and the Pacific Ocean in summer (Fig. 4).

3.2. Transport pathways and potential sources

Here, we will discuss the potential PM$_{10}$ transport pathways in Shanghai based on the results of backward trajectory cluster analysis, TSA and PSCF. High PM$_{10}$ concentrations in the TSA sectors indicate highly polluted pathways, while high PSCF values indicate potential emission sources.

3.2.1. The northwestern pathway: cluster #2 (the Mongolian high) and cluster #3 (the Mongolian cyclone and Northeast China low)

The northwestern pathway was based on cluster #2 and cluster #3 from the northwestern (inland) directions (Figs. 4 and 5). By comparison, cluster #2 moved at a much higher speed and therefore, had a longer mean trajectory than cluster #3. Trajectories in cluster #2 primarily occurred in winter, followed by spring and autumn. And cluster #3 prevailed in winter and spring, followed by autumn. The occurrence frequencies of cluster #2 and cluster #3 reached their lowest points in summer (Fig. 6).

In winter, East Asia is affected by the strong Mongolian cold high that originates from the cold Siberian high-pressure and Aleutian low above the northern Pacific Ocean. Northerly winter monsoons prevail in continental China (Zhang and Lin, 1985). The strong Mongolian cold high may contribute to cluster #2, which was characteristic of a northwestern direction, high moving direction and high frequency of occurrence in winter. Taken together, these factors indicate that cluster #2 might be due to the Mongolian high.

The second northwestern pathway of cluster #3 is characteristic of northwesterly direction and a relatively high and constant frequency all year except in summer. The two features showed that cluster #3 may be due to the Mongolian cyclone and the Northeast China low. The Mongolian cyclone occurs throughout the year, with a higher frequency of occurrence in spring, and usually moves eastward, subsequently forming the Northeast China low (Zhang and Lin, 1985). Because Shanghai is located southwest of the Mongolian cyclone and the Northeast China low, cluster #3 was likely influenced by the two cyclone systems.

In conclusion, cluster #2 was primarily due to the effect of the Mongolian cold high, while cluster #3 was primarily due to the Mongolian cyclone and Northeast China low.

The PM$_{10}$ concentration of cluster #3 was the highest of the seven clusters (98.1 $\mu$g/m$^3$), followed by cluster #2 (91.7 $\mu$g/m$^3$) (Fig. 7). Trajectories in cluster #3 traveled through Hebei, Shandong, Shanxi and Jiangsu. These cities were all significant anthropogenic sources of PM$_{10}$ (Fig. 8), with a total PM$_{10}$ emission load higher than 1000 Gg/yr (Zhang et al., 2009a). Although cluster #2 was also affected by the highly polluted areas along the pathway, the high speed of cluster #2 resulted in greater dispersion of air pollutants.

High relative contributions of PM$_{10}$ were found in sectors 11 and 12 (Fig. 9), reflecting the highly polluted nature of the northwestern pathway. The PSCF result (Fig. 10) also showed high values in the southeast of Hebei, Shandong and Jiangsu, which indicates the potential sources (S1) for these areas.

3.2.2. The northeastern pathway: cluster #1 (the polar high)

The northeastern pathway was based on cluster #1 (Figs. 4 and 5). Trajectories in this pathway mainly originated from the northeastern and northern directions (Fig. 5). The northeastern pathway occurred during nearly the entire year in Shanghai, except in summer, reaching its lowest activity in July. Additionally, the occurrence frequency of this pathway peaked in September and October (Fig. 6).

This pathway may be affected by the anticyclone circulation of polar high pressure in Mongolia and Siberia. The Mongolian high occurs throughout the year, and its intensity changes seasonally (Zhang and Lin, 1985). The Polar high resulted in a northerly wind and caused cluster #1 to maintain a constant and high frequency in winter and spring, but not during summer, when the Indian Low Pressure and Subtropical High controlled China Mainland. In addition, autumn is a transition season from the summer monsoon to winter monsoon. In autumn, the Mongolian high begins to form, and its border influences the Southeast China coastal area (Zhang and Lin, 1985). In sum, the frequency of cluster #1 reached its peak value in autumn.

Trajectories in cluster #1 originated from the Korea Peninsula and moved southwest through the southern portion of the Yellow Sea. Northeastern winds from the Yellow Sea are oceanic but may not necessarily be clean because the air masses over the Yellow Sea could contain continental outflow and polluted discharge from northeastern China (Ichoku et al., 2004; Fang et al., 2006). The moderate PM$_{10}$ concentration of 80.5 $\mu$g/m$^3$ (Fig. 7) for cluster #1 may result...
Fig. 5. 72-hour backward trajectories within the seven clusters.
from the mixture of the polluted northeastern air with the clean marine air.

According to the TSA results, sector 1 and sector 2 made a relatively moderate contribution to the PM$_{10}$ concentration in Shanghai (Fig. 9).

3.2.3. The southeastern pathway: cluster #6 (the Western Pacific high)

The southeastern pathway is based on cluster #6 (Figs. 4 and 5). Trajectories in cluster #6 were found primarily in summer, especially in July and August, and might be affected by the summer monsoon. After April, the Mongolian high and Aleutian low grow weaker, while the Indian low and Western Pacific high gradually increase their effect on East Asia. In July and August, the Asian continent is completely controlled by the Indian low and the Subtropical high above the western Pacific Ocean (Zhang and Lin, 1985). Affected by the anticyclonic circulation in the southeast region of Asia, southeastern winds prevailed on the east coast in summer, referred to as the southeast monsoon (the subtropical monsoon component) (Wang et al., 2002). The southeastern direction and high frequency in summer indicated that cluster #6 was due to the Western Pacific high.

Additionally, in summer typhoons frequently hit the southeast coastal area of China (Zhang and Lin, 1985). We found that the average moving speed of trajectories in cluster #6 increased dramatically and could reach 14 m/s on days with recorded typhoons. Hence, cluster #6 might also be affected by typhoons in summer.

Because the air masses in cluster #6 originated from the western Pacific Ocean, cluster #6 may represent the effect of relatively clean marine air masses. Moist air masses from the sea also caused the formation of precipitation and subsequent wet deposition of PM$_{10}$ (Yan, 1996). However, the western Pacific Ocean was also affected by the outflow of air pollutants emitted through industrial pollution and dust emission in northern Asia as well as biomass burning in southeast Asia (Chin et al., 2004; Chou et al., 2002; Chu et al., 2005; Lin et al., 2007), especially in spring and winter. High concentrations of PM$_{10}$ were found in the coastal region of Southeast and East Asia (Chou et al., 2002; Li et al., 2003a, 2003b; Lin et al., 2007). Hence, the path of cluster #6 (70.8 μg/m$^3$) was not completely unpolluted. However, this relatively clean pathway in summer still contributed to the low PM$_{10}$ concentration observed in Shanghai (Fig. 3) (Lin et al., 2007).

Average PM$_{10}$ concentrations and relative contributions in sector 5 were low (Fig. 9). Furthermore, PSCF values along the pathway were high over the sea but relatively high near the coastal region.
The average PM$_{10}$ concentration for cluster #7 was high at 91.5 μg/m$^3$. The relative contribution of PM$_{10}$ from sector 7 reached its peak value in the south of Shanghai (Fig. 9). The PSCF method also identified a potential source of PM$_{10}$, including Zhejiang, Fujian, northwestern Guangdong and eastern Jiangxi (S2) (Fig. 10).

According to the results of TSA, the relative PM$_{10}$ contribution of sector 12 (cluster #1 and cluster #2) was nearly twice that of sector 7 (cluster #4). In other words, the PM$_{10}$ contribution of the northwestern source (S1) was approximately twice that of the southwestern source (S2).

3.2.6. The eastern pathway: cluster #5 (transition of monsoons)

The eastern pathway is based on cluster #5 (Figs. 4 and 5). Cluster #5 occurred over a long period of time, ranging from March to October, with its peak activity found from April to June and August to October (Fig. 6). The frequency distribution of cluster #5 indicated that it might be associated with the transition of monsoons.

In April to June, the atmospheric circulation was transitioning from the winter monsoon to the summer monsoon. Some researchers refer to this period as the pre-monsoon season. In April/May, the southeastern flow related to the subtropical high over the western Pacific was strong, but the southwestern wind over tropical Asia was very weak, and the summer monsoon over India, Southeast Asia and the Yangtze River valley was not yet established. Simultaneously, the westerly wind over North Asia and the North Pacific was dramatically weaker in summer relative to winter. Under the influence of the strong subtropical monsoon and the weak tropical monsoon, the flow pattern in April/May is characteristic of eastern and southeastern wind (Wang et al., 2002). Similar to the atmospheric circulation pattern in spring, the atmospheric circulation pattern in autumn transitioned from summer monsoon to winter monsoon. Eastern and northeastern winds prevailed in August to October (Wang et al., 2002).

Air masses in cluster #5 originated from southwest Japan and moved westward to Shanghai. The PM$_{10}$ concentration of this cluster was 74.9 μg/m$^3$, reflecting that the cluster carried clean maritime air mass to Shanghai. The PM$_{10}$ concentrations and relative contributions for sectors 3 and 4 of the TSA were both at low values (Fig. 9). This was consistent with the result of the cluster analysis.

4. Conclusions

In this study, backward trajectory cluster analysis, TSA and PSCF methods were used to investigate the transport pathways and potential sources of PM$_{10}$ in Shanghai. The analyses were based on backward trajectories that were calculated using HYSPLIT4 and PM$_{10}$ monitoring data from 2006 to 2009.

Seven clusters were generated from backward trajectory cluster analysis. Among these clusters, three corresponded to the winter monsoon and were generated by the Asian mainland high pressure in winter and the Mongolian cyclone. These clusters provided a main mechanism for transporting air pollutants of North China to Shanghai. The other three southerly pathways were associated with the summer monsoon caused by the subtropical anticyclone over the
western Pacific Ocean on the eastern coastal area and the Indian low in spring and summer. The remaining cluster indicated the transition of monsoons. Two potential sources were identified from the PCSC method. One was the northwestern source, including Hebei, Shandong, Anhui and Jiangsu, which mainly affected Shanghai in winter and spring when northerly air flow transported high-concentration PM$_{10}$ to Shanghai. The other potential source originated in the southwestern region, including Zhejiang, Jiangxi and Fujian, which primarily affected Shanghai in summer.

According to the results of TSA, the relative PM$_{10}$ contribution of the northwestern sources was approximately twice that of the south-western sources. This was consistent with the high concentration of PM$_{10}$ measured in winter and spring.

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