Analyzing Regional Inluence of Particulate Matter on the City of Beijing, China

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Abstract

The concentration levels of particulate matter (PM) in the city of Beijing (39.92°N, 116.46°E), China are dependant on the long-range transport of PM in addition to local stationary and mobile sources. To analyze the regional influences of PM_{10} on the city of Beijing for the year 2004, 366 back trajectories were generated using Hybrid Single-Particle Langragian Integrated Trajectory modeling. The trajectories were then characterized by regions traversed 24 hrs back in time. The comparative impact scores of the trajectories were calculated based on the emission rates of PM_{10} and its precursors in each region the trajectories traversed as well its distance to Beijing. For the purpose of the subject analysis, the 366 days in 2004 were categorized as good (< 50 μg/m^3), moderate (50-150 μg/m^3), and poor (> 150 μg/m^3) air quality groups based on daily PM_{10} concentrations. Besides Hebei which surrounds Beijing in all directions, our results identified Inner Mongolia, Shanxi, and Mongolia as regions having greater influence on Beijing air quality due to the prevailing westerly and northwesterly winds. Overall, the higher the overall impact score of a particular trajectory cluster, the larger the probability of having poor air quality days and the smaller the probability of having good air quality days. The analysis also indicates that on an annual basis, when air masses travel from Shanxi, which is home to many coal-fired power plants, Beijing tends to have poor air quality due to high PM_{10} concentrations. In comparison, when air masses originating over Inner Mongolia, where anthropogenic emissions are low, Beijing tends to have good PM air quality. However, our case study showed that during the spring, air masses originating over Inner Mongolia and Mongolia tend to carry dust and sand to Beijing, leading to poor PM air quality.

***Keywords**:* Air quality; Atmospheric aerosols; PM_{10}; Regional transport; Trajectory modeling.

INTRODUCTION

Particulate matters (PM) are small solid or liquid particles suspended in ambient air. The

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term PM_{10} refers to fine particles or droplets that are 10 microns or less in aerodynamic diameter. The composition of PM_{10} mainly depends on its sources. PM_{10} originated from wind-blown dust tends to be made of mineral salts and other crystal material. Primary emissions from combustion sources are largely unburned fuel (e.g. hydrocarbons), elemental carbon (i.e. soot), mineral salts, and often contain traces of toxic metals. PM can also be formed through chemical transformation of gaseous pollutants, the so-called secondary pollutants, which includes ammonium, sulfite, nitrite salts and their complex compounds, and organic carbon. In most urban areas, dust from paved and unpaved roads, construction and demolition sites, and bare fields are contributors to PM_{10} as well (Ho *et al.*, 2003). The human health effects of inhaling particulate matter include asthma, lung cancer, cardiovascular disease, and premature death (EPA, 2006).

Beijing (39.92°N, 116.46°E), the capital city of China, is in the northeast region of China, as shown in Fig. 1. A combination of rapid industrialization, a large population of 14.6 million and high population density has inevitably drawn more attention to the air pollution issues, one of which is PM_{10} (SEPA, 2005; BJEE, 2007; Zhang *et al.*, 2007). In Beijing, major local PM sources include coal combustion, industry and motor vehicle emissions, road dust, as well as secondary aerosol (Sun *et al.*, 2004).

The PM level in a city depends not only on local emissions but also on regional emissions and meteorological factors. More specifically, the city of Beijing is downwind of Shanxi (Fig. 1), which is one of the largest coal mining and coal-fired power generation provinces in China (Zhao, 2004). Other provinces surrounding Beijing (Fig. 1) are also heavy emitters of air pollutants (Wang *et al.*, 2005). In addition to anthropogenic emissions, in the spring there are frequent occurrences of northeast Asian dust and sand storms, which originate in dry regions like the Taklamakan Desert of China and the Gobi Desert of China and Mongolia. The areas affected are often across northeast Asia (Huang, 2006). The sand storms are sometimes so intense that the region suffers severe economical loss due to low visibility and the adverse health effect of high PM levels. A study of sand storms in 2004 found that only Beijing was affected by extreme pollution, amongst the forty-seven seriously affected cities (PureInsight, 2005), likely due its close proximity to the Gobi Desert. An analysis of the transport and sources of PM_{10} in Beijing during spring 2001-2003 suggests a significant contribution of Asian dust (Wang *et al.*, 2004).

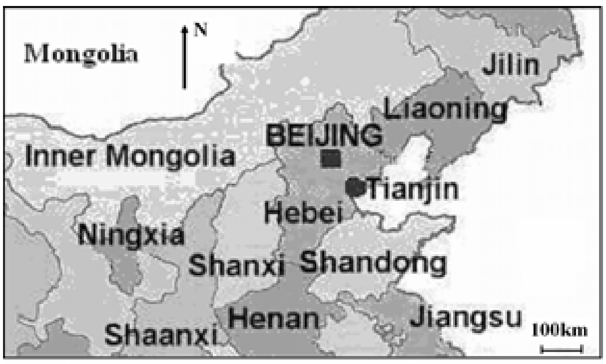

Fig. 1. Map of Beijing, China and its surrounding areas (Adapted from: http://www.chinatour.com/maps/maps.htm).

As a result, Beijing's neighboring regions can make significant contributions as the sources of PM and its precursors. The challenge is how to distinguish locally generated PM and PM transported into the area. There are techniques for assessing the local and transported PM. For instance, intensive monitoring with fine spatial and/or temporal resolution can identify regional trends and hot spots (Chow *et al.,* 1996). Potential source contribution function analysis and incremental probability analysis can identify likely areas of regional influence (Wang *et al.,* 2004; Brown *et al.,* 2007). Examination of chemical components can be used to identify the consistency of sources within a given region (Zhang and Friedlander, 2000). The use of "tracers-of-opportunity" or species ratios accompanied by trajectory analysis is another method, such as using potassium and other species to identify forest fire impact (CAPITA, 1999). Source apportionment studies can also identify potential major source sectors (e.g., Zelenka *et al.,* 1994; Watson and Chow, 2002). Satellite images have been used to track the PM transport, for example, to link Saharan dust storm to elevated PM levels in the United States (EPA, 2007).

The objective of this study is to investigate the impact of meteorology and neighboring regions on PM levels in Beijing, using an innovative approach. Daily PM_{10} air quality data in 2004 were analyzed in conjunction with trajectory modeling as well as emission inventory, by employing an "overall impact score" of the trajectory. A case study was also conducted to analyze the effect of the major sand and dust storms on Beijing PM air quality. This paper summarizes the major findings.

METHODS

PM_{10} data and air quality categories

The daily PM_{10} Air Quality Index (AQI) data collected at Changpingzhen Air Quality Monitoring Site, Changping District, in 2004 were obtained from the Beijing Environmental Protection Bureau website (BJEPB, 2007). The Air Quality Index (AQI) values were converted to PM_{10} concentration in μg/m^3 using the Air Quality Index Equations (BJEE, 2007).

For the purpose of the subject analysis, in this study the China National Ambient Air Quality Standard's (SEPA, 1996) first-class category (0-50 μg/m^3) was termed as good, and the second-class (50-150 μg/m^3) as moderate air quality. In order to have a sufficient sample size for statistical analysis, the rest of the three categories of Chinese AQI were grouped and termed as poor air quality with PM_{10} concentration greater than 150 μg/m^3.

HYSPLIT simulation and analysis

Three hundred and sixty-six backward trajectories, one for each day, were generated for the year 2004 using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003; Rolph, 2003). For each modeling run, a 48-hr HYSPLIT backward trajectory was modeled with Changpingzhen, Changping District, Beijing, China, as the starting point. Changpingzhen Site was selected because it is northwest of downtown Beijing hence upwind of the prevailing westerly and northwesterly air mass arriving in the city. Additionally, it is fairly far away from major transportation routes, industrial and agriculture sources. Therefore, this site is more representative of regional transport in comparison with other locations. The 48-hr time scale was chosen to consider regional transport of air pollutants. Because it may take a few hours to a few days for particulate matter to settle, while NO_x, SO_x, and VOCs (volatile organic compounds) may travel for up to three days (Seinfeld and Pandis, 1998). These trajectories were used to reconstruct air parcel movements, back in time from the Changpingzhen (Changping District, Beijing) air quality-monitoring site.

The meteorological dataset of Global Reanalysis for the year 2004 was used. The horizontal resolution of the Global Reanalysis data is 2.5-degree latitude and longitude with 6-hour spacing (NOAA, 2003). The staring time of 11:00 UTC (i.e. 19:00 local time) was used because the hourly PM_{10} typically reach the highest concentrations at 6-8 pm in Beijing (Zhang *et al.*, 2007). A release height of 300 m above ground level was selected to account for the wind shear aloft that affects the air mass path of regional and long-range transport (NOAA, 1999). In addition, a recent study found that the air parcel arriving at Beijing was impacted by the transfer of pollutants from regional sources at the layer of 325 m in height, while the lower layers (8, 100 and 200 m) were more affected by Beijing's local sources (Chan *et al.*, 2005).

Each of the HYSPLIT modeling output represents an aerial plot of trajectory arriving at Changpingzhen, Beijing. Some of the trajectories were identified to loop back on themselves. For this reason, the 48-hr trajectory was divided into two sub trajectories as 0-24 hrs and 24-48 hrs to have a more relevant estimated direction attempting to avoid the frequent changes in direction and looping. The 0-24 hrs subtrajectory, the one closer to Changpingzhen, was considered to carry out the analysis.

A single trajectory typically passed through more than one province/region before reaching Beijing. The regions that each trajectory traverses 1-24 hrs before reaching Beijing were identified and recorded, following Anastassopoulos *et al.* (2004). Analyzing the area traversed by the air mass trajectories can provide valuable information about the possible source regions of PM_{10}. For example, if an air parcel originated from Inner Mongolia and the receptor is in Beijing, the air parcel may carry pollutants from Shanxi, Hebei as it passes over those areas. Therefore, the frequency distribution of regions traversed by the trajectories was calculated, on all days in 2004, and on good as well as poor air quality days.

Emission and regional impact assessment

It is important to clarify that the possible source regions identified through trajectory analysis or the incremental probability method does not necessarily denote that a region is making a significantly negative contribution to Beijing's air quality. In order to identify source regions that are responsible for PM_{10} air quality in Beijing, published emission rates of all the regions that those trajectories traverse before reaching Beijing were complied. Total emission estimates of PM_{10}, NH_3, NO_x, SO_2, and NMVOCs (non-methane volatile organic compounds) of the source regions were considered for this purpose. The inclusion of NH_3, NO_x, SO_2, and VOCs emissions in addition to PM_{10} is because these pollutants are the precursors of particulate matter (Chow *et al.*, 1996). The emission estimates (kton per year) of these pollutants for the provinces of Shanxi, Shandong, Henan, and Hebei were obtained from Wang *et al.* (2005) for the year 2000. The emissions for Mongolia, Inner Mongolia, and Liaoning were estimated from a study by Streets *et al.* (2003). Those emission inventories were the most recent data by province the authors could find in the public domain.

Furthermore, the emission amount alone cannot adequately reflect the impact of a region on Beijing's air quality, since atmospheric processes such as wet and dry deposition will remove PM_{10}. Thus, the distance of each region to Beijing was considered as well, because the impact of a source region to a receptor site is likely to decrease with increasing distance. The distances were measured using Google Earth (Google Earth, 2007). As the province of Hebei (Fig. 1) surrounds Beijing, an average distance between Hebei and Beijing was obtained. For each region, the total emission rate of PM_{10} and its precursors was divided by the distance from Beijing to calculate an impact factor, because the impact of an area should be proportional to its amount of emissions and inversely proportional to its distance to the receptor.

Moreover, if an air parcel trajectory travels over more than one source area, the probability of carrying and transporting pollutants to Beijing is larger. In order to assess the overall impact of a single trajectory, the impact factors of all provinces traveled by that particular trajectory were summated to obtain an overall impact score. For example, if a trajectory pathway had crossed Shanxi that has an impact factor of 4, and Hebei, which has an impact factor of 2; the trajectory's overall impact score is 4 + 2 = 6. Note that an overall impact score of six may result from a very different trajectory. Therefore, the predominant trajectory in every "overall impact score set" was identified by calculating the percentage of a particulate trajectory's occurrence in that "overall impact score set".

The average concentrations and the percentages of the poor and good air quality days associated with each trajectory group were calculated and analyzed. The relationship between the overall impact scores of the trajectories and the daily PM_{10} air quality in Beijing was investigated to evaluate the comparative effect of source regions on Beijing's air quality.

RESULTS AND DISCUSSION

PM_{10} characteristics

Time series of daily PM_{10} concentrations in Beijing is plotted in Fig. 2 to identify the trend and seasonality for the year 2004. January, February, March, April, October, November,

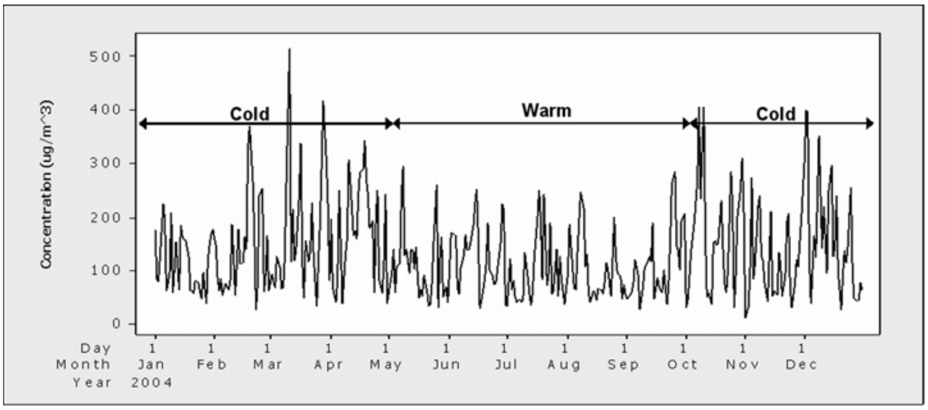

Fig. 2. Time-series plot of daily PM_{10} concentration for the year 2004.

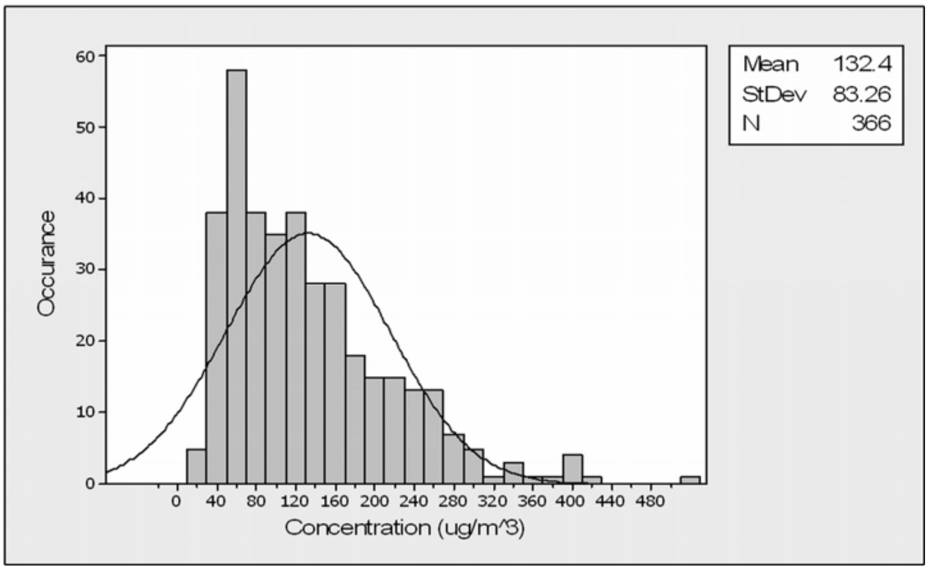

Fig. 3. Distribution of daily PM_{10} concentrations.

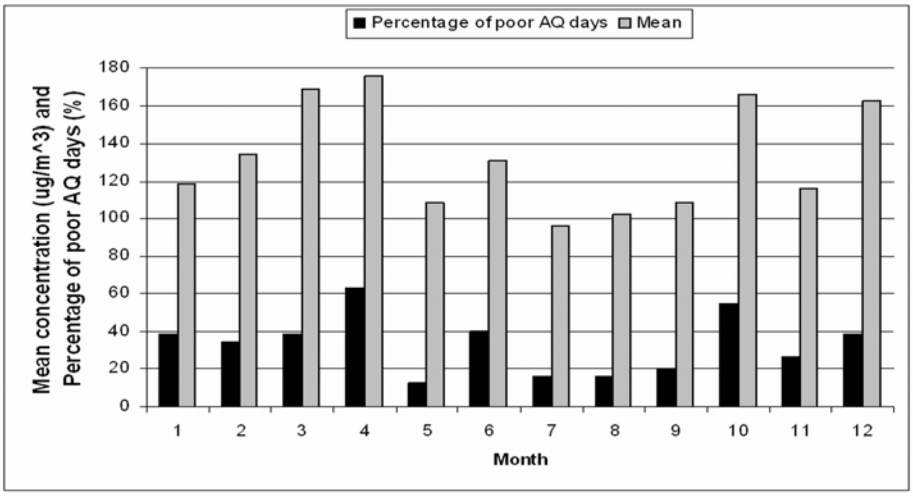

Fig. 4. Monthly percentage of poor air quality days and mean PM_{10} concentration.

Table 1. Impact factor of the provinces/area affecting Beijing air quality.

Province /Area	[a]NH_3	[a]NOx	[a]PM_{10}	[a]SO_2	[a]NMVOC	Total Emission Rate (Kton/year)	Distance (km)	Emission Rate/Distance (kton/yr.km)	Impact Factor
Shandong	1,645	1,174	9,539	1,756	1070	15,184	380	40	4
Hebei	1,173	1,337	12,906	1,928	759	18,103[b]	175	41	4
Shanxi	288	807	5,346	1,087	353	7,881	390	20	2
Henan	1,267	993	7,486	1,775	704	12,225	690	18	2
Liaoning	288	807	5,346	1,087	353	7,881	630	13	1
Inner Mongolia	<30	<30	<27	<30	<30	<147	450	0.33	0
Mongolia	~0	<30	<27	<30	<30	<117	1,200	0.10	0

[a] Sources: Wang et al. (2005) and Streets et al. (2003).

[b] 40% of the emission rate was used in emission rate/distance calculation.

December were termed “cold season” by observing both the daily PM_{10} concentration data and meteorological information, while May, June, July, August and September were termed “warm season”.

The daily PM_{10} concentrations in 2004 appeared not to be a normal distribution, as shown in Fig. 3. The highest frequency occurred between 50 to 70 µg/m^3. The average concentration of PM_{10} was 132 µg/m^3 with a standard deviation of 83 µg/m^3. In the year 2004, 45 (12.3%), 199 (54.4%), and 122 (33.3%) days were found to be in the good (> 50 µg/m^3), moderate (50-150 µg/m^3), and poor (> 150 µg/m^3) air quality groups respectively. During the cold season, there are more poor air quality days (42.3%) leading to a mean concentration of 149 µg/m^3. The average concentration was lower in the warm season (109 µg/m^3), with less frequent poor air quality days (20.9%). The higher PM_{10} concentrations in the cold season is caused by the combination of low mixing level, persistent temperature inversions and increases in emissions related to heating (Ye *et al.,* 2003).

The percentage of poor air quality days and mean concentration in each month is shown in Fig. 4. It can be observed that in the months of April and October of 2004, Beijing experienced high PM_{10} concentrations, and the air quality was poor in over 50% of days in those months. The month of April in particular, had consecutive days of high PM (Fig. 2) thus the highest monthly concentration in 2004 as shown in Fig. 4, likely due to blowing dust and sand storms; more analysis on this is to follow.

Top regions influencing beijing air quality

The frequency of occurrences of the regions influencing Beijing’s air quality is shown in Fig.

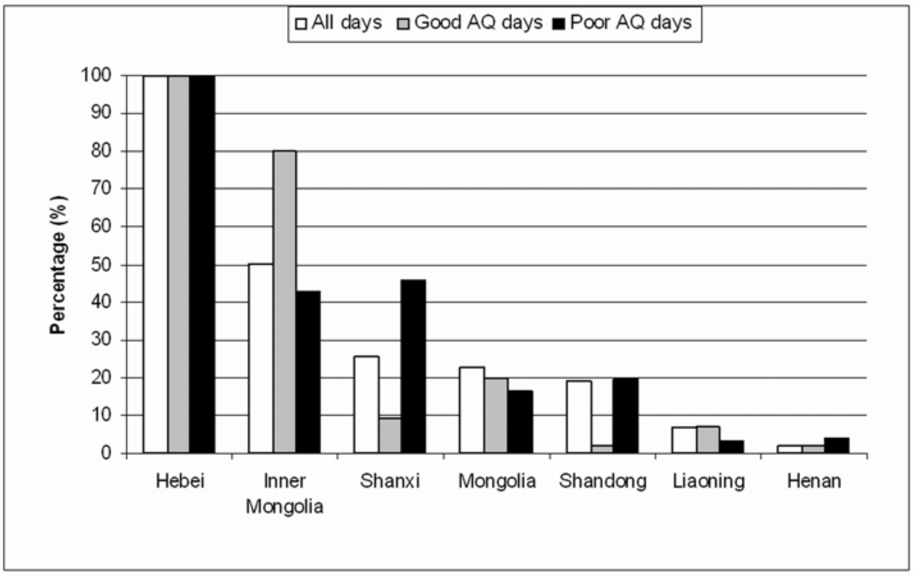

Fig. 5. Regions influencing Beijing PM air quality.

5. For all days in 2004, Hebei, the province that surrounds Beijing in all directions, was found to be the most frequent region to influence Beijing's air quality, as expected. Also shown in Fig. 5, Beijing air quality is most often influenced by Inner Mongolia, Shanxi, and Mongolia due to the prevailing westerly and northwesterly winds. Fig. 5 also shows the frequency of occurrences of the provinces influencing Beijing PM air quality when it was poor (> 150 $\mu g/m^3$) or good (< 50 $\mu g/m^3$). The difference between the meteorological transport patterns on all days and on poor or good air quality days helps identify the regional influence. As shown in Fig. 5, air masses from Inner Mongolia tend to lead to good air quality days on an annual basis. On the other hand, the incremental probability of poor air quality is most pronounced for Shanxi, suggesting strong influence by this province that is home to a large number of coal-fired power plants. It should be noted that the reported emission from Shanxi is not very high (Table 1). However, the mountains in the Shanxi-Hebei-Beijing transport corridor could prevent fast dispersion of pollutants.

Table 1 lists impact factors of each province/area that the 366 trajectories traverse.The highest impact factor is 4, which was assigned to Shandong, largely due to high emissions. Both Henan and Shanxi have an impact factor of 2 because of the high emission rates of Henan, and close distance between Beijing and Shanxi, respectively. A factor of 1 was assigned to Liaoning which has a middle level emission rates but is fairly far way from Beijing. Mongolia and Inner Mongolia's impact factor was zero for low anthropogenic emissions. As Beijing is surrounded by Hebei, at any given time, at least half of the province is downwind of Beijing. Thus, only 40% of the emission rate was counted in this analysis. As a result, an impact factor of 4 was assigned to Hebei.

Table 2. Predominant trajectory within each "overall impact score set".

Overall Impact Score (#of days)	Trajectory	# of days and % in that 'Overall Impact Score set'	Predominant Trajectory
4 (170 days)	Mongolia→ Inner Mongolia→ Hebei→ Beijing	79 days, 46.5%	(Mongolia)→ Inner Mogolia→Hebei→Beijing
	Inner Mongolia→ Hebei→Beijing	76 days, 44.7%	
	Hebei only→ Beijing	15 days, 8.8%	
5 (24 days)	Liaoning→ Hebei→ Beijing	18 days, 75.0%	Liaoning→ Hebei→ Beijing
	Inner Mongolia→ Liaoning→ Hebei→ Beijing	6 days, 25.0%	
6 (101 days)	Shanxi→ Hebei→ Beijing	66 days, 65.3%	Shanxi→ Hebei→Beijing
	Inner Mongolia→ Shanxi → Hebei→Beijing	27 days, 26.7%	
	Henan→ Hebei→ Beijing	8 days, 7.9%	
8 (71 days)	Shandong→ Hebei→ Beijing	71 days, 100.0%	Shandong→ Hebei→ Beijing

The predominant trajectory in each "overall impact score set" was identified as shown in Table 2. The overall impact scores of the 366 trajectories arriving at Beijing were between 4 and 9. Of the 366 trajectories, almost half (46.4%) had an overall impact score of 4 which is (Mongolia)-Inner Mongolia-Hebei, while 6.6, 28.9, and 18.9 % had an overall impact score of 5 (Liaoning-Hebei), 6 (Shanxi-Hebei), and 8 (Shandong-Hebei), respectively for the year 2004 as shown in Fig. 6a. The Liaoning-Shandong-Hebei trajectory scored 9 but occurred only once on April 29, 2004, leading to a very high PM_{10} concentration of 242 μg/m^3. Because of its low frequency, this trajectory was combined with Shandong-Hebei (scored 8) in further analysis. The frequency of trajectories, however, changed significantly with season. During the cold season (Fig. 6b), (Mongolia)-Inner Mongolia-Hebei is the most frequent trajectory (56.3%), followed by Shanxi-Hebei (35.2%). In the warm season (Fig. 6c), the Shandong-Hebei and (Mongolia)-Inner Mongolia-Hebei trajectory each occurred approximately one-third of the time, with fewer occurrences in the trajectories of Inner Mongolia-Shanxi-Hebei (17.6%) and of Liaoning-Hebei (11.8%). Due to the low occurrence of the Liaoning-Hebei trajectory (score 5), further analysis is to focus on the

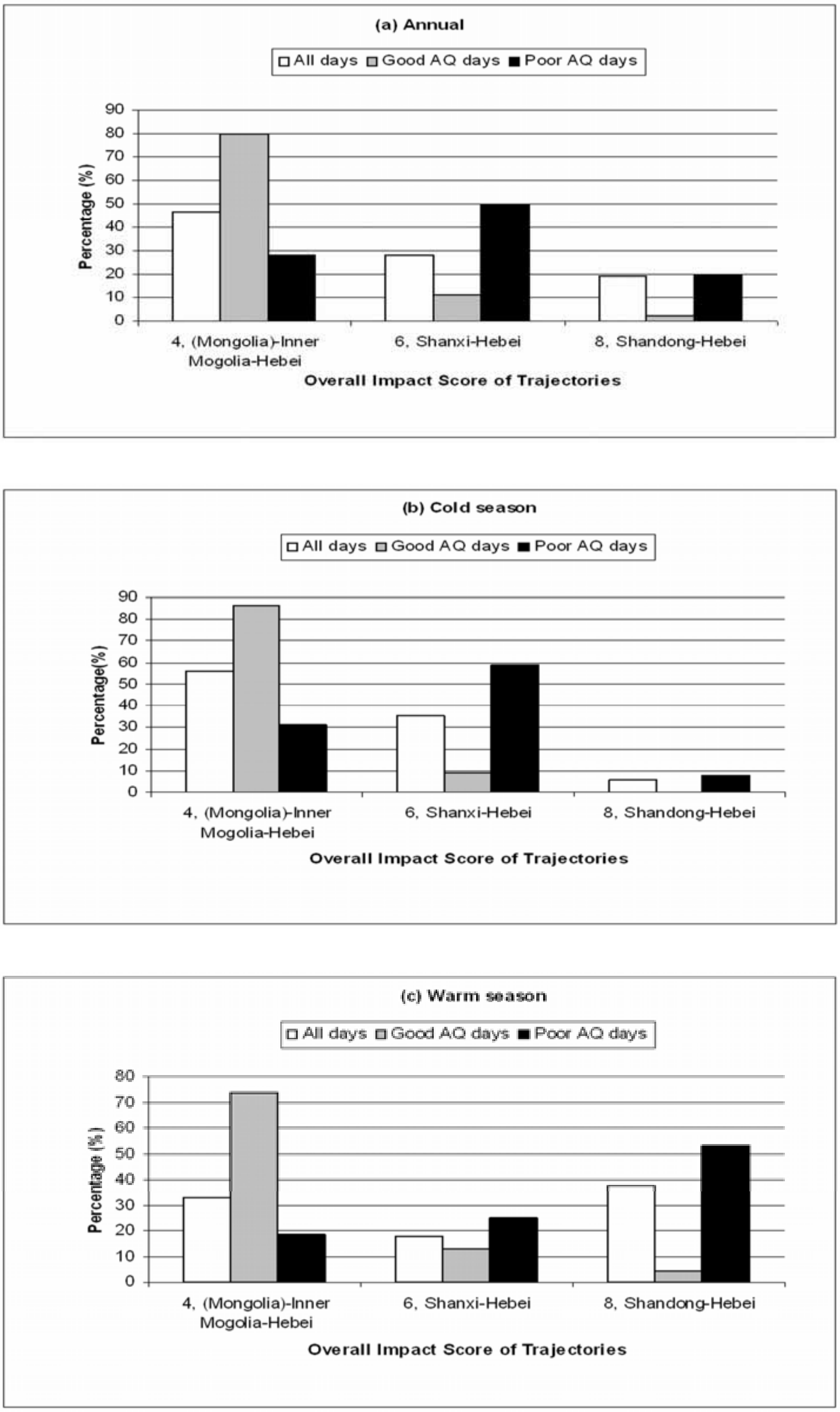

Fig. 6. Percentage of all days, good and poor air quality days for each overall impact score trajectory set in (a) the year of 2004, (b) cold season, and (c) warm season.

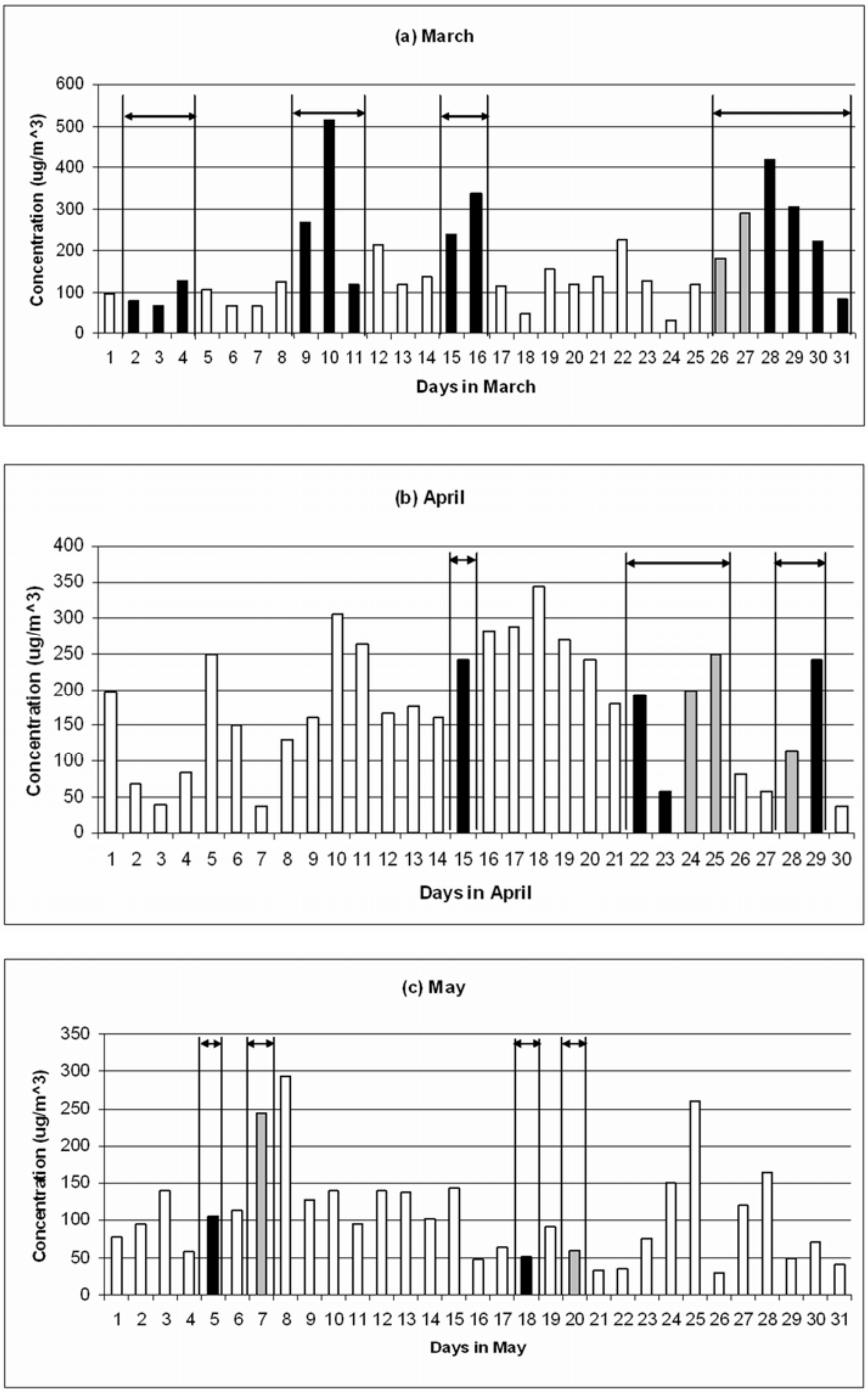

Fig. 7. Sand and dust storm event days and Beijing PM_{10} concentration in the month of (a) March, (b) April, and (c) May. Days encompassed between the vertical lines represent sand or dust storm event. Black: one or more of the regions on trajectories were affected by sand and dust storms; grey: none of the regions on the trajectories was directly affected.

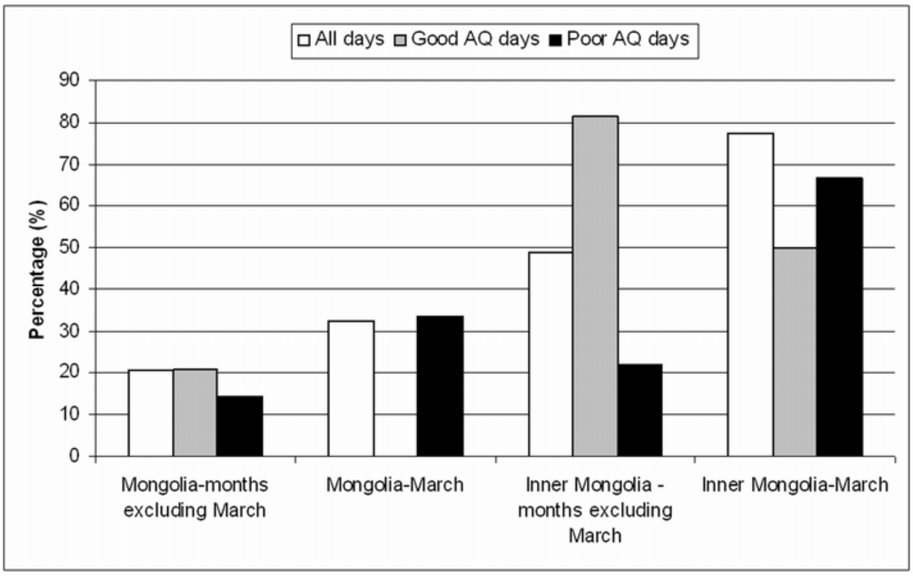

Fig. 8. Comparison of March and other 11 months in 2004, percentages of all, good and poor air quality days.

other three groups which scored 4, 6, and 8, respectively.

The comparison between meteorological transport patterns, on all days and on good or poor air quality days, is also depicted in Fig. 6. On the annual basis (Fig. 6a), 50% of poor PM days could be attributed to the Shandong-Hebei trajectory (score 8), while the (Mongolia)-Inner Mongolia-Hebei trajectory (score 4) resulted in 80% of good air quality days. In the cold season (Fig. 6b), nearly 60% of the poor PM days can be attributed to the Shanxi-Hebei trajectory (score 6), whilst the Shandong-Hebei trajectory (score 8) seemed responsible for over half of poor PM days in the warm season (Fig. 6c). Overall, a clear trend was observed, i.e. the higher the overall impact score, the larger the incremental probability of having poor air quality days; while the lower the overall impact score, the larger the incremental probability of having good air quality days.

During the spring of 2004, 15 sand and dust storms occurred in and across China; 13, 7 and 4 days in March, April and May respectively; all 15 events originated in the Mongolia or Inner Mongolia region (SEPA, 2005). Fig. 7 shows the daily PM_{10} concentrations in March, April and May, with the event days marked. It was identified when Beijing was affected by the sand and/or dust storms from the Mongolia and Inner Mongolia regions, PM_{10} concentrations raised noticeably, e.g. March 15-16 and April 24-25, or significantly (e.g. March 9-10) and poor air quality often resulted. In some events, the peak PM_{10} in Beijing had a one-day lag behind the sand storm, e.g. April 23-24. In the month of April, PM_{10} concentrations were high on most days even with the absence of sand or dust storms. The effect of transport from the Mongolia and Inner Mongolia sector is further evident in Fig. 8. In contract to the rest of the year, in March the air mass originating over

Mongolia and Inner Mongolia occurred more often, and those air masses resulted in more frequent poor air quality days.

It is noteworthy that year 2000 emission inventory was used in this study due to the absence of emission data by province in 2004. China experienced rapid economic growth during the period of 2000 to 2004 and sequential increases in air emissions (NAE and NAS, 2007). The nationwide SO_2 emissions increased more than 10% from 2000 to 2004, while the soot and industrial dust emissions decreased slightly (SEPA, 2005; NAE and NAS, 2007). Nonetheless, the authors believe that the rank order by total emission rates of the areas involved in this study would not differ significantly from 2000, therefore, the relative scores of the predominant trajectories would not change significantly in the four years.

In future studies of regional influences of PM, a number of other factors could also be investigated. Meteorological parameters such as precipitation events (i.e. the removal of PM) and ambient temperature that affects various chemical conversion rates, and frontal systems that frequently lead to low pollutant concentrations, could be considered. Wind speed can also influence the transport and fate of particulate matter. PM_{10} concentration tends to decrease initially with wind speed due to improved ventilation in an area, and then increases at higher wind speeds due to increased suspension of soil particles (Chow *et al.,* 2000). Additionally, some large regions could be divided into small segments to obtain more accurate emission rates. Moreover, the mixing of anthropogenic emissions with sand dust particles could be investigated (Zhang *et al.,* 2006). Furthermore, the stationary and mobile emission rates and mass balance inside Beijing can be carried out to quantify local contributions. Intra-city variability or hot spots that occur in major urban industrial areas and near transportation corridors are beyond the scope of this study. Nonetheless, these kinds of information are critical in human exposure assessment and emission control policy-making.

CONCLUSIONS

In this study, the HYSPLIT back trajectory model and emission inventory were used to identify the regional influence on the PM_{10} in the city of Beijing, China. The results identified Hebei, Inner Mongolia, Shanxi, and Mongolia as regions having a greater influence on Beijing's air quality, primarily due to the prevailing winds. It was also found that a higher "overall impact score" of a particular trajectory leads to a higher probability of poor air quality days in Beijing. It can be concluded that the emission rates of PM as well as its precursors and the distance to Beijing can be used as an indicator of that trajectory's impact on Beijing's air quality. For the year of 2004, a higher percentage of poor PM_{10} days in Beijing is expected when air masses are passing over Shanxi; while when air masses originate over Inner Mongolia, Beijing tends to have good air quality in terms of PM_{10}. However, in March Mongolia and Inner Mongolia had a negative impact on Beijing air quality. This deviation from the annual trend is largely due to the effect of dust and sand storm events originating in the Mongolia and Inner Mongolia region.

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