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An Integrated MM5-CAMx Modeling Approach for Assessing PM_{10} Contribution from Different Sources in Beijing, China

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ABSTRACT. In this study, a coupled MM5-CAMx air quality modeling system is proposed for simulating the PM_{10} (which stands for the suspended particulate matter less than 10 μm in diameter) concentration in Beijing, China. The PSAT (particulate matter source apportionment technology) technique is used to investigate the PM_{10} source apportionment in this area. The results indicate that the influence from regions outside of Beijing including Hebei province, Shanxi province, Tianjin city, and Inner Mongolia cannot be ignored, and the total emission source contribution ratio (ESCR) from these regions is 26.65%. Emissions from four local industries in Beijing including stationary emission source, road dust emission source, construction sites dust emission source, and fugitive industrial emission source, which has an ESCR of 59.59%, are main local contributors of PM_{10}. Further analysis shows that these four industry emissions located in the urban area of Beijing are main contribution sources of PM_{10} pollution in Beijing, with an ESCR of 51.67%. The results obtained can provide useful information for Beijing's PM_{10}-emission control and abatement. They can also be used for further pollution-mitigation plans establishment and providing a solid support for sound air quality management.

Keywords: air quality, CAMx, MM5, PM_{10}, PSAT

1. Introduction

Airborne particulate matter is an important air pollution issue in many cities which is linked to health problems, and causes degradation in visibility and is a source of acid deposition (Hopke et al., 2008). As a result, many source apportionment methods and techniques were introduced into Gaussian models, Lagrangian puff models and trajectory models (Holloway et al., 2002; Begum et al., 2005; Fushimi et al., 2005; Lee et al., 2007; Anastassopoulos et al., 2008) to determine the major emission source categories and emission source regions that contribute to primary particulate matter. However, in the Gaussian, Lagrangian, and trajectory approaches, emissions from multiple separated sources were assumed to be not interacted; this assumption was not effective for the secondary PM pollutants (e.g., sulfate, nitrate, ammonium, secondary organic aerosol). Although the Puff models could be used for estimating the secondary PM, it was based on dramatically simplifying the chemistry of secondary PM formation to eliminate interactions. These techniques could not be used for accurately determining the source regions of secondary particulate matter because non-linear chemical transformations were difficult to be expressed. Secondary PM pollutants, whose formation is governed by atmospheric chemistry, are important components of fine particulate matter and cannot be ignored in atmosphere. Therefore, Eulerian photochemical grid models were extensively used for modeling secondary pollutants (Morris et al., 2006; Tesche et al., 2006). For example, (Chen et al., 2007b) developed a community multi-scale air quality model (CMAQ) to determine the source regions of particulate matter at Beijing in North China. Four different simulations when the particulate matter emission from each of the four source regions was removed separately from the emission inventory were compared with the baseline simulation to determine the contribution of each source region to the particulate matter concentration at a receptor site in Beijing. However, this method was very time intensive and only applicable to the pollutants and/or precursors sources that did not have a significant feedback on the non-linear photochemical formation of secondary pollutants.

Reactive tracer methods (also named as tagged species methods) can effectively overcome this limitation by adding extra species to the grid model to trace the contributions of specific sources. The main challenge in developing the reactive tracer methods is assigning the effects of nonlinear chemistry, which are calculated for the total concentration fields, to the reactive tracers for individual sources. Recently, a source appor-

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tionment technique based on reactive tracers was expanded by researchers at UC Riverside (EPA grant # R832163) to track the formation of secondary pollutants (Ying and Kleeman, 2009). This technique was integrated into the community multi-scale air quality (CMAQ) modeling system and termed the tagged species source apportionment (TSSA) (Tonnesen et al., 2005). In addition, a technique named particulate matter source apportionment technology (PSAT) based on the reactive tracer methods was implemented in CAMx to provide source apportionment for primary and secondary PM species to geographic source regions, emissions source categories, and individual sources. The PSAT was effective for identifying what sources contribute significantly to PM and visibility problems and designing the most efficient and cost-effective PM and visibility control strategies.

Previously, a number of research works were undertaken to investigate the air pollution problem in the City of Beijing, the capital of China. For example, through meteorological diagnose, Su et al. (2004) found that local valley wind, the thermal islands, and thermal and dynamical circulation of the low pressure under the background of the weak pressure and even pressure field were the major cause of forming the pollutants transportation convergence problem in Beijing and North China Plan. Pollutants trans-boundary transportantion is a main factor of Beijing air quality problem. Chen et al. (2007a) used the measured lidar data and model simulation result confirmed the pollutants trans-boundary transport in Beijing from surrounding provinces by the southwest winds. Chen et al. (2007b) and Streets et al. (2007) also applied MM5-CMAQ model system to estimate the PM_{10}, $PM_{2.5}$ and O_3 trans-boundary contributions in Beijing from surrounding provinces and cities, respectively. Besides, source-receptor study of PM_{10} air pollution problem in Beijing has been implemented. Cheng et al. (2007b) proposed a coupled MM5-ARPS-CMAQ air quality modeling system to investigate the contribution of various emission sources to the air quality in Beijing, and found that fugitive industrial emissions, construction sites dust, and road dust were three major sources to the PM_{10} pollution in Beijing. Wang et al. (2008) proposed the positive matrix factorization (PMF) model to study the source apportionment of $PM_{2.5}$ and PM_{10} in Beijing, and conformed that coal combustion was the largest contributor of $PM_{2.5}$ and soil dust was the largest contributor of PM_{10}. Westerdahla et al. (2009) used the monitoring data to study the on-road vehicle emission factors and characterize transportation-related air pollution in different types of micro-environments in Beijing. In addition, the relationship between particulate matter and public health risk in Beijing was studied by Zhou et al., (2003). The analysis of simulated, optimized and monitored data could provide solid support to establish environmental policy planning for air quality management (Athanasiadis and Mitkas, 2007; Yeomans, 2008). In general, although many research efforts were conducted for mitigating the air pollution in Beijing, the city still faces a variety of challenges in air quality management issue (Hao et al., 2005). For example, in 2007, the annual average of PM_{10} concentration was 148 μg/m^3, which is substantially higher than the National Air Quality Standard (Class II Annual Average Level) of 100 μg/m^3 (BJEPB, 2008). Therefore, a more effecttive approach is desired to help reduce emissions in Beijing and its surrounding areas and thus maintain the local air quality at a safe level.

The objective of this study is to develop a coupled MM5-CAMx air quality modeling system for simulating the PM_{10} concentration in Beijing. Moreover, the PSAT technique will be used for investigating PM_{10} source apportionment in the study region. Comparing with the previous study, this technique can deeply illustrate the PM_{10} contribution from different regions and industries. The PM_{10} contribution from regions nearby Beijing, local industries emission sources in Beijing, and main local industries emission sources from different regions in Beijing will be analyzed, such that the main regions and industries which have great effects on PM_{10} concentration in Beijing will be selected. Then, an efficient and cost-effective control strategy can be implemented by controlling PM_{10} emission from these main regions and industries.

2. MM5/CAMx Air Quality Modeling System

The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) is a limited-area, nonhydrostatic, terrain-following sigma-coordinate method designed to predict mesoscale and regional-scale atmospheric circulation (Dudhia et al., 2004). This method has advantages including (1) a multiple-nest capability, (2) nonhydrostatic dynamics, which allows the model to be used at a few-kilometer scale, (3) multitasking capability on shared and distributed memory machines, (4) four-dimensional data-assimilation capability, and (5) more physics options. Currently, MM5 has been widely used for mesoscale convective system, fronts, land-sea breezes, mountain-valley circulations, and urban heat islands (Grell et al., 2000; Chen and Dudhia, 2001a, b).

The comprehensive air quality model (version CAMx4.4) is an Eulerian photochemical dispersion model that allows for integrated "one-atmosphere" assessments of gaseous and particulate air pollution (ozone, $PM_{2.5}$, PM_{10}, and air toxics) over many scales ranging from sub-urban to continental (ENVIRON, 2006). It is designed to unify all the technical features required of "state-of-the-science" air quality models into a single system that is computationally efficient, easy to use, and publicly available. CAMx can be provided environmental input fields from any meteorological model (e.g., MM5, RAMS, and WRF) and emission inputs from any emissions processor (e.g. SMOKE, CONCEPT, EPS, EMS). In addition to the features shared with most photochemical grid models, there are some other notable features of CAMx: (1) two-way grid nesting, (2) flexi-nesting, which allows for reconfiguration of nested grids during a simulation, (3) multiple gas phase chemistry mechanism options (CB4, CB05, SAPRC99), (4) evolving multi-sectional or static two-mode particle size treatments, (5) plume-in-grid (PiG) module for sub-grid treatment of selected point sources, (6) probing tools, such as ozone/particulate source apportionment technology (OSAT/PSAT), decoupled direct method (DDM) for source sensitivity of ozone and other species, process analysis (PA), and

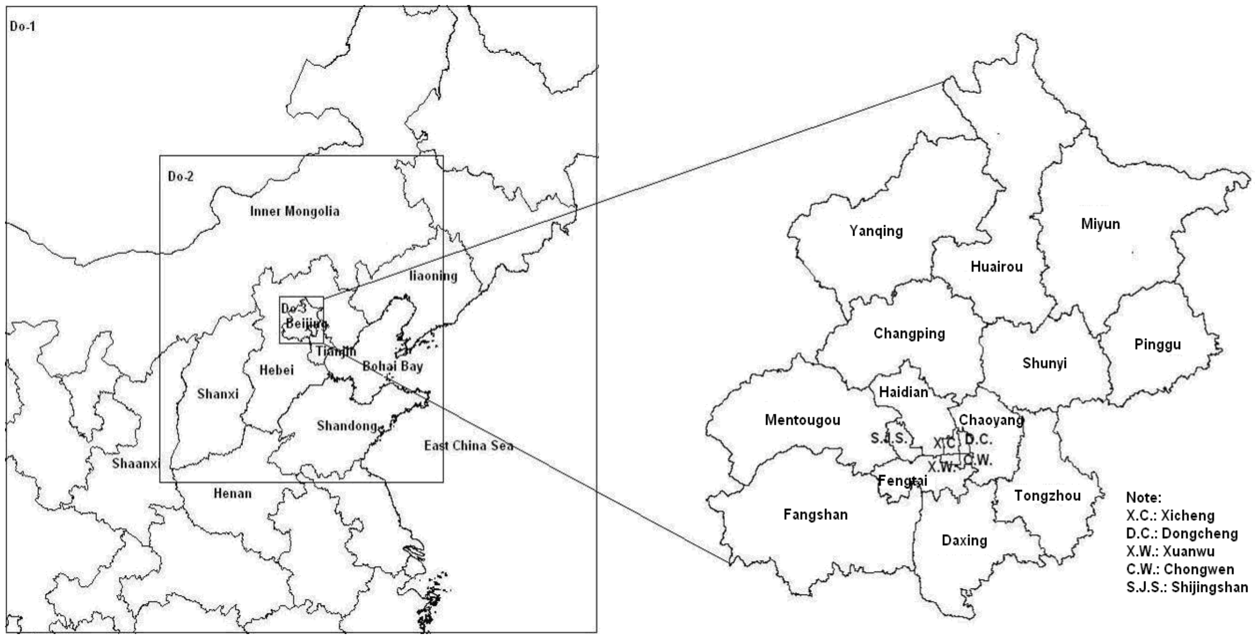

Figure 1. The designed 3-level nested domain architecture for Beijing and its surrounding provinces.

reactive tracer (RTRAC) source apportionment for air toxics, (7) mass conservative and consistent transport numerics, and (8) parallel processing using Open-MP. Because of above features, since 1996, CAMx has been employed extensively by local, state, regional, and federal government agencies, academic and research institutions, and private consultants for regulatory assessments and general research throughout the U.S. Currently, CAMx has been used on nearly every continent for 1-hour and 8-hour ozone, local PM and regional haze, oil & gas development, toxics, and mercury pollution simulation and control strategy research (Dunker et al., 2002; Wagstrom et al., 2008; Yarwood et al., 2008).

In this study, particulate matter source apportionment technology (PSAT) will be introduced into the CAMx to provide source apportionment for primary and secondary PM species to geographic source regions, emissions source categories, and individual sources. PSAT was developed from the related ozone source apportionment method (OSAT) already implemented in CAMx (Dunker et al., 2002), and the advantages of PSAT are expected to be high efficiency and flexibility to study the source apportionment from different source categories and regions.

PSAT source apportionments are calculated using reactive tracers that operate in parallel to the main CAMx calculations for total species concentrations, which means selecting PSAT does not alter the CAMx calculations and results for total PM species concentrations. PSAT is implemented in CAMx for the following types of particulate matter (PM): sulfate, nitrate, ammonium, mercury, secondary organic aerosol (SOA) and six categories of primary PM, including elemental carbon (EC), primary organic aerosol (POA), crustal fine (2.5 μm), other fine, crustal coarse (2.5 - 10 μm), and other coarse. For each class of PM, PSAT includes reactive tracers for the PM species (e.g., sulfate) and any related precursor species (e.g., SO_2). PSAT apportions PM species to their corresponding precursor sources: sulfate (PSO_4) is apportioned to sources of SO_2; nitrate (PNO_3) is apportioned to source of NOx; ammonium (PNH_4) is apportioned to source of NH_3; SOA (SOA1-SOA5) is apportioned to the corresponding VOC precursors (Yarwood et al., 2005).

Adding PSAT tracer species to a CAMx simulation, by selecting the PSAT option, increases the resource requirements for CPU, memory and disk storage. PSAT is less demanding of CPU and disk resources than alternate approaches such as zero-out analysis. To provide flexibility in managing the resource requirements the PSAT apportionments for each class of PM species may be selected independently for each simulation. For example, you can apportion just sulfate, or sulfate/nitrate/ammonium, or just primary PM, or all types of PM, etc. The application tests confirmed that PSAT is computationally more efficient than zero-out analysis. The run-time speed-up ranged from factors of about 9 for SOA to 30 for sulfate (Yarwood et al., 2005). SOA is less efficient than sulfate because more tracer families are required (14 vs. 2 tracer families).

3. Case Study

3.1. Overview of Study Area

Beijing is situated at 40 degrees north latitude and 116 degrees of longitudes (39º08' ~ 41º05' N, 115º25' ~ 117º30' E), with Tianjin City on its eastern border and Hebei province on its other three sides (as shown in Figure 1). Other surrounding provinces include Inner Mongolia to its north, Shanxi province and Shaanxi province to its west, Henan province to its south, Shandong province to its southeast, and Liaoning province to its northeast. Beijing covers an area of 16,800 square kilometers,

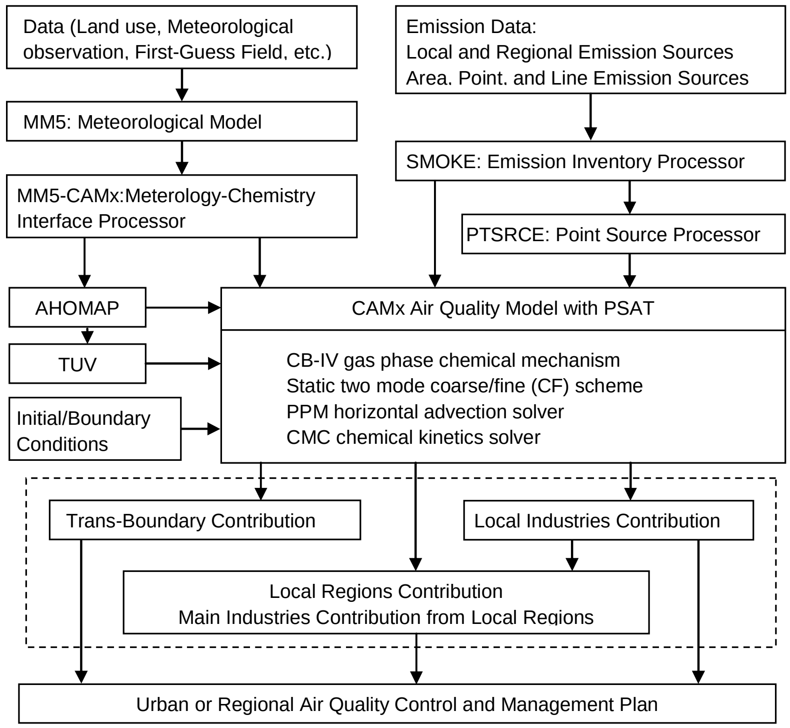

Figure 2. The schematic of MM5-CAMx modeling system.

of which 38% is plain and 62% is mountain. There are 16 subordinate districts and two counties within the municipal boundary under the jurisdiction of the Metro Beijing, with a total population of around 14 millions in the year of 2002. In addition, Beijing is surrounded by the Yan-Shan and Tai-Hang Mountains, and its air quality is affected by meteorological and environmental conditions both locally and regionally.

In the past decades, much effort has been made to improve the air quality in Beijing. Since December 1998 the Beijing municipal government has implemented 15 stages of comprehensive emergency control measures to mitigate the SO_2, NOx and PM pollution. Especially after the successful bid of the 2008 Beijing Olympic Summer Games in July 2001, the government has taken much strict efforts to lift air quality so as to achieve one key concept of Beijing 2008 Olympic Games – "Green Olympics". For example, the city has used various subsidies, fines, administrative (disposal) charges and other economic measures to encourage the use of clean fuels among enterprises and citizens; Beijing has been leading the country in implementing stricter emission standards than the state benchmarks to reduce vehicle emissions; Beijing has plans to phase out coal use through changing the energy structure of the whole city; it also has significantly expanded the coverage of grass and trees for preventing wind erosion of soil from bared ground surface. And during the period of Beijing Olympic Games, Beijing and surrounding regions had taken critical measures, like close major emission facilities, cease the work in construction sites, limit vehicles running time to better achieve "Green Olympics" goal.

Although air pollution in Beijing has obviously been mitigated since 1998, it still faces a long way and big challenges in air quality improvement (Hao et al., 2005). In 2007, the annual average of PM_{10} concentration was 148 $\mu g/m^3$, which is substantially higher than the National Air Quality Standard (Class II Annual Average Level) of 100 $\mu g/m^3$ (BJEPB, 2008). So, detail research of the source-receptor relationship to the air quality in Beijing is urgently needed to further improve air quality, especially in the post-Olympic age when much critical effort had been made to reduce emission in Beijing and surrounding regions.

3.2. Application

In this study, MM5 model with FDDA was used for developing the meteorological fields for CAMx. As shown in Figure 1, three nesting levels with spatial resolutions of 27, 9 and 3 km, respectively, on a Lambert map projection centered at (40° N, 116° E) were designed for this study.

The outermost domain (D-1), for MM5, with a spatial resolution of 27 × 27 km covering most areas of northeastern China was established with a dimension of 84 × 84 grid cells. The middle domain (D-2), for CAMx, with a spatial resolution of 9 × 9 km covering Beijing and most areas of its surrounding provinces was established with a dimension of 132 × 144 grid cells. The innermost domain (D-3), for CAMx, with a resolution of 3 × 3 km covering the entire Beijing metropolitan region was established with a dimension of 62 × 62 grid cells. MM5 was setup to simulate meteorological parameters in outermost domain, middle domain, and innermost domain, and CAMx was setup to simulate air quality only in middle domain, and innermost domain. The total plain areas of middle and innermost domains for CAMx were 1,188 × 1,296, and 186 × 186 km^2, respectively. The middle domain for MM5 was 5 grids more than that for CAMx in each direction, and the innermost domain for MM5 was 3 grids more than that for CAMx in each direction, in order to minimize the side effects at the boundary of the meteorological models. Vertically, 35 layers were identified and spaced unevenly from the ground to a height of 15 km in MM5, among which 20 layers were distributed within a height of 2 km from the ground in order to provide specific planetary boundary information. The 35 layers were merged into 12 layers vertically when applying the CAMx for air quality simulation.

Figure 2 shows a schematic diagram of the integrated MM5-CAMx modeling system. In this integrated framework, the CAMx modeling system requires 4D meteorological data which were provided by the MM5 mesoscale meteorological model, and emission inventory data which were generated by SMOKE (Sparse Matrix Operator Kernel Emissions Modeling System) and a module named PTSRCE from REMSAD (the Regional Modeling System for Aerosols and Deposition). Among the various modules included in the integrated system, the MM5-CAMx module converted the MM5 outputs to the CAMx required inputs, including landuse, height and pressure, wind, temperature, water vapor, cloud and rain, and vertical diffusivity. Besides AHOMAP program prepared albedo/haze/ozone column data for CAMx, and TUV program developed photolysis rate data for CAMx CB4 photochemical mechanism.

The combined MM5-CAMx numerical system provided advantages in predicting pollution dispersion over complex terrain, since MM5 calculations of the near-surface meteorological fields (including vertical turbulence) were used as input in CAMx to estimate the concentrations of fine and total PM (Titov et al., 2007). Physical options used for MM5 were: (1) MRF planetary boundary layer model; (2) Grell cumulus scheme; (3) Dudhia simple ice moisture scheme; (4) cloud radiation scheme, and (5) Noah Land-Surface Model. CAMx was configured with the following options: (1) two-way grid nesting; (2) CB-IV gas phase chemical mechanism with the static two mode coarse/fine (CF) scheme; (3) Piecewise Parabolic Method (PPM) horizontal advection solver; and (4) CMC chemical kinetics solver.

The required topography data used for MM5 was obtained from the Digital Elevation Model from USGS with a spatial resolution of 30s, and the land-use data was also obtained from the USGS's 1-km NOAA/AVHRR satellite data sets. The 3-D first-guess meteorological fields for modeling were obtained from the Global Tropospheric Analyses datasets provided by the US National Center for Environmental Prediction, and were available every 6 hours with $1^o \times 1^o$ resolution. The observational meteorological data were provided by the China Meteorological Administration, which was available every 3 hours for ground surface and every 12 hours for soundings. During the MM5 model run, the program automatically searched for the meteorology observations in the dataset within the domain defined. Initial and boundary conditions for the chemical species modeled were based on the default values distributed with the CAMx model. The daily global ozone column data as Earth Probe TOMS (Total Ozone Mapping Spectrometer) was obtained from NASA to provide parameters for spatial and temporal variation of photolysis rates.

The emission inventory is the basis dataset for Beijing PM_{10} air quality simulation and PSAT study. Several emission datasets were used by the coupled modeling system. A relatively detailed emission inventory of air pollutants (with most of the required species included) were obtained from the environmenttal protection administrations of Beijing, and were used as a primary dataset for the grid cell over the study area. The emission inventories of Beijing's surrounding provinces (with few species included, mainly PM and SO_2) at a county level were obtained from the environmental protection administrations of these provinces. The NO_X emissions and anthropogenic nonmethane volatile organic compounds (NMVOC) emissions from the surrounding provinces were taken from the emission inventories prepared by Streets et al. (2003). The biogenic VOCs emission was obtained from GEIA (Global Emission Inventory Activity) (Benkovitz et al., 1995). These emission inventories were processed by the modified SMOKE model (Houyoux and Vukovich, 1999). Then emission processor SMOKE and module PTSRCE were used for area and point emission inventory dataset to obtain high spatial and temporal resolution emission inputs required by CAMx.

3.3. Setup for PSAT

The PM_{10} air pollution problem in Beijing is complex. In this study, three steps by using PSAT technique to better illustrate the relationship between emission and contribution in Beijing in November 2002 were established. Comparing with the other conventional methods, this method can indicate the relationship between emission sources and contribution values in a more detailed way, reduce the error in nonlinear simulation and shorten the time for simulation and result analysis.

As showed in Figure 1, the study area contains Beijing and its surrounding provinces and cities, including Tianjin, Hebei, Shanxi, Shaanxi, Inner Mongolia, Liaoning, Shandong, and Henan. In the first step, the study area is divided into 8 regions and 1 industry site, as showed in Table 1, to analyze the trans-boundary contributions for the surrounding provinces and cities. In the second step, the study area is divided into 2 parts which are Beijing and region surrounding of Beijing. Emission from 7 industries (stationary emission source, fugitive industrial emission source, construction sites dust emission source, road dust emission source, bare land emission source, vehicle exhaust emission source, and resident energy consumption emission source) in Beijing were analyzed to estimate the contributions from local industries of Beijing and to find out the main contribution industries in Beijing. In the final step, the study area is divided into 14 regions and 5 industries (which were determined in the second step as main contribution industries), to evaluate contributions from different regions of Beijing and assess the main industries' contribution from different regions of Beijing.

Table 1. Setup Parameters for Three Step PSAT Simulation Scenarios

No	Number of industries	Number of regions	Details of the regions
1	1	8	1:Beijing, 2:Tianjin, 3:Hebei, 4:Shanxi, 5:Inner Mongolia, 6:Liaoning, 7:Shandong, 8:Other regions（Henan and Shaanxi）
2	7	2	1:Beijing, 2:reigon outside of Beijing (including Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Shandong, Henan, and Shaanxi)
3	5	14	1: urban center of Beijing (including Dongcheng, Xicheng, Chongwen, and Xuanwu), 2:Chaoyang, 3:Fengtai, 4:Shijingshan, 5:Haidian, 6:Mentougou, 7:Fangshan, 8:Tongzhou, 9:Shunyi, 10:Changping, 11:Daxing, 12:Huairou and Yanqing, 13:Pinggu and Miyun, 14: reigon outside of Beijing (including Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Shandong, Henan, and Shaanxi)

4. Results and Discussion

4.1. Modeling Performance

In order to evaluate the performance of the MM5-CAMx modeling system, we compared the simulated PM_{10} concentrations with the ground-based observations in Beijing. For represent a good spatial coverage of the urban area of Beijing, seven air quality monitoring stations located within the urban area of Beijing were selected, including AoTi, CheGongZhuang, DongSi, GuCheng, NongZhanGuan, QianMen and TianTan. The observed hourly PM_{10} results from these seven monitoring stations were averaged and then compared with the predicted hourly PM_{10} concentration in the urban area of Beijing. The agreement between predicted PM_{10} concentrations and measured data was evaluated and quantified statistically by the scatter plot diagram.

Figure 3 displays the scatter plots and the correlation analysis results of hourly PM_{10} concentrations from the average of these seven monitoring stations and from the MM5-CAMx modeling predictions by using SPSS® statistical software. The $y = x$ line on the scatter diagram represents perfect agreement between the two data sets. A pair value (or a pair dot) above the $y = x$ line indicates a situation of over prediction and values below the line indicate under-prediction. In general, Figure 3 shows that most of the scatter plots are adjacently distributed on both sides of $y = x$ line or on the line in November, which does highlight a consistent over- and under- prediction for PM_{10} concentration. Considering inherently uncertain nature associated with the meteorological and air quality prediction, this fluctuation demonstrates that the accuracy of model prediction is acceptable and the performance of the coupled modeling system is acceptable as well. The Pearson correlation coefficient is 0.723 under the 0.01 significance level for November. Therefore, a satisfactory agreement has been reached between the modeled value and the observed data.

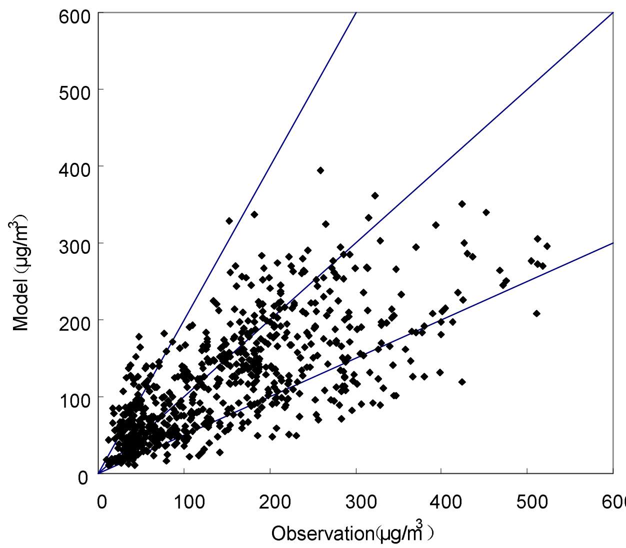

Figure 3. Scatter plots of simulated versus observed PM_{10} concentrations in November 2002.

Table 2. Simulated Monthly PM_{10} ESCRs from Different Sources (%)

Region	ESCR
Beijing	72.27
Tianjin	2.24
Hebei	20.41
Shanxi	2.79
Inner Mongolia	1.21
Other	0.79
IC	0
BC	0.29

4.2. Impacts of Trans-Boundary Pollution on Beijing's Air Quality

In the first PSAT setup the study area of North China was divided into 8 regions to better illustrate the PM_{10} regional emission source contribution ratio (ESCR) from area outside of Beijing. Table 2 shows the PSAT simulation result that Beijing PM_{10} concentration is greatly influenced by Beijing (local) and Hebei (regional) emissions. The mean monthly ESCRs were 72.27% from Beijing, 2.24% from Tianjin, 20.41% from Hebei, 2.79% from Shanxi, 1.21% from Inner Mongolia, 0.79% from other region, and 0.29% from the boundary condition, respectively, and with a total ESCR of 27.73% for region outside of Beijing. Therefore, Tianjin, Hebei, Shanxi and Inner Mongolia were main PM_{10} contribution regions outside of Beijing, with a total ESCR of 26.65%. The contribution of these four main regions would be discussed detailed below.

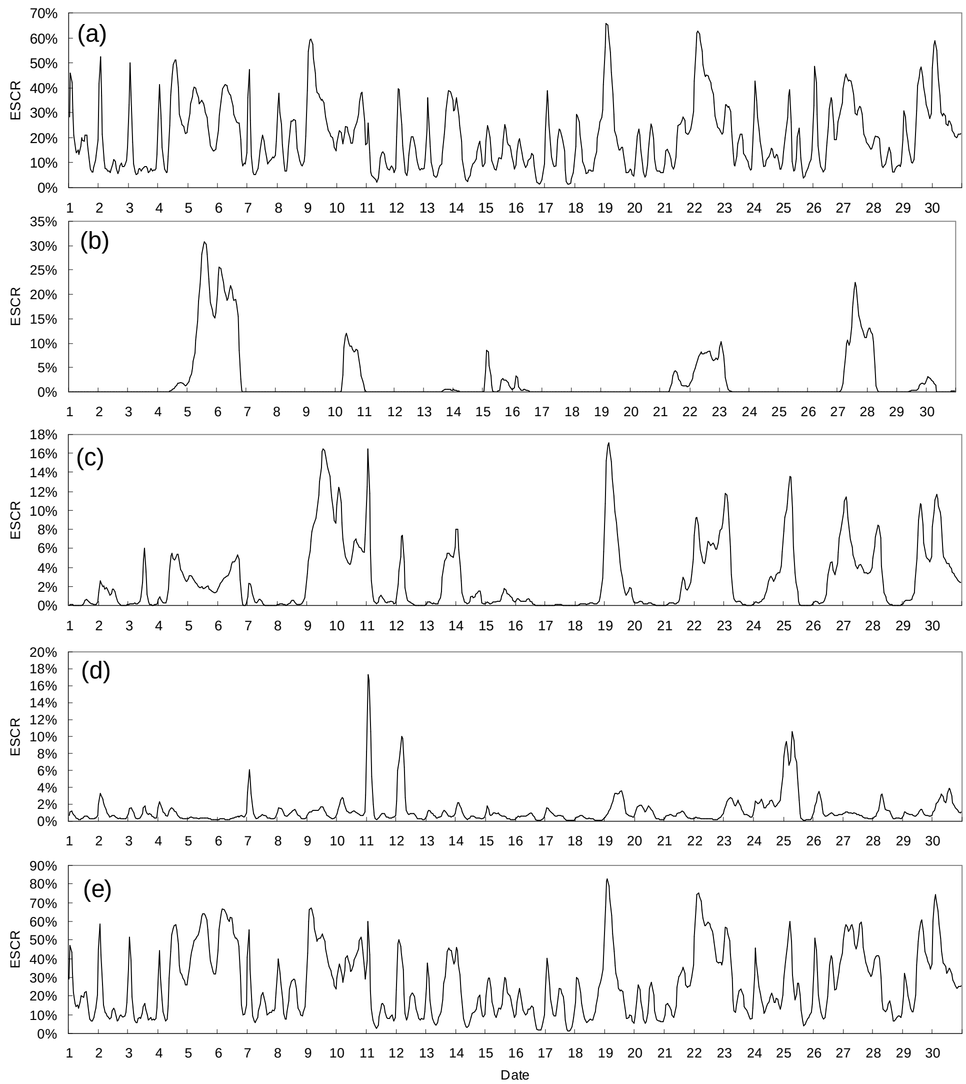

Figure 4. Simulated hourly PM_{10} ESCRs from major regions outside of Beijing: (a) Hebei, (b) Tianjin, (c) Shanxi, (d) Inner Mongolia, and (e) Four main regions outside of Beijing.

Hebei which surrounds Beijing is a geographically important province in northern part of the North China Plain. The total area of this province is 187,693 square kilometers and at the end of the year 2002 the total population is 67.35 million. Hebei has highly developed agriculture, and now is one of the major coal producers, iron industry and pottery manufacturing, petrol-chemicals, chemicals, and building materials producers regions in China. Figure 4(a) displays the PM_{10} ESCR curves from Hebei, which shows high hourly ESCR during November and the maximum hourly ESCR is up to 65.68%.

Tianjin, located in northeast part of the North China Plain, is 130 kilometers away from the southeast of Beijing. The total area of Tianjin is 11,920 square kilometers and at the end of the year 2002 the total population is 10.07 million. Tianjin is one of the biggest industrial and port cities in China, and is famous of auto and machinery manufacture, chemicals, and metallurgy. Figure 4(b) displays the PM_{10} ESCR curves from Tianjin, which shows interval hourly ESCR in November. In most time of November the hourly ESCR from Tianjin is near zero, but in some time hourly ESCR is increase greatly, and the maximum ESCR is up to 30.88%.

Shanxi, bounded by the North China Plain in the east and the middle Yellow River in the west, is located on the west of the Hebei province. The total area of this province is 156,300 square kilometers and at the end of the year 2002 the total population is 32.94 million. Shanxi is the base of coal industry, and is an important region of iron and steel, electric power, chemical, textile and food industry. Figure 4(c) displays the ESCR curves from Shanxi, which shows the hourly PM_{10} ESCR in November is changed greatly, and the maximum ESCR is up to 17.06%.

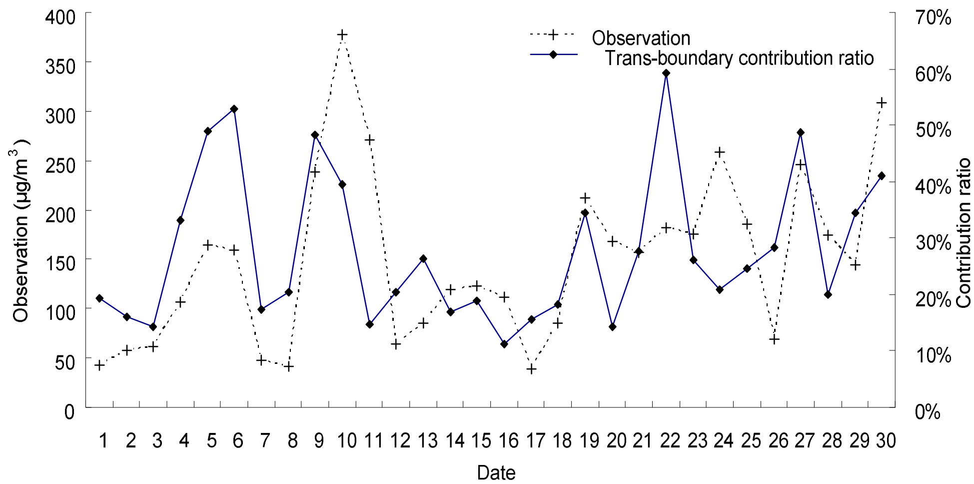

Figure 5. Comparison of the monitored daily PM_{10} concentration curve with the simulated daily trans-boundary contribution ratio.

The Inner Mongolia Autonomous Region, China's northern border autonomous region, is on the north of Hebei province. The total area of this province is 1.18 million square kilometers and at the end of the year 2002 the total population is 23.79 million. Inner Mongolia abounds in natural resources especially mineral resources, and now also engages in forestry, coal mining, steel and power plants industries. Figure 4(d) displays the ESCR curves from Inner Mongolia, which shows the hourly PM_{10} ESCR in November is not very high, and the maximum ESCR is up to 17.35%. Figure 4(e) displays the PM_{10} ESCR curves from all these four main region outside of Beijing, including Hebei, Shanxi, Tianjin and Inner Mongolia, which shows high hourly ESCR during November and the maximum hourly ESCR is up to 82.78%.

Figure 5 presents comparison of the monitored daily PM_{10} concentration curve with the simulated daily PM_{10} transboundary contribution ratio which includes ratios from the regions outside of Beijing, including Tianjin, Hebei, Shanxi, Inner Mongolia, Other Region, BC and IC. It is obvious to see that the monitored daily PM_{10} concentration trend matches the simulated daily contribution ratio curve quite well, especially for the periods when PM_{10} pollution episodes occurred, like day 5 and 6, 9 and 10, 19, 22, 27, and 30 in November, monitored daily PM_{10} concentration and simulated daily contribution ratio increased synchronously. This phenomenon proved that transboundary contribution played a crucial role in forming PM_{10} pollution in Beijing. The average simulated daily trans-boundary contribution ratio for days when PM_{10} pollution episodes occurred is 34.76%, much more than the monthly contribution ratio 27.73% in November. The Maximum simulated daily PM_{10} trans-boundary contribution ratio is 59.28% in day 22 when monitored daily PM_{10} concentration is up to 182.3 $\mu g/m^3$ as lightly to heavily polluted air quality. The Maximum simulated hourly PM_{10} trans-boundary contribution ration is 83.21% in day 19 when monitored daily PM_{10} concentration is up to 211.6 $\mu g/m^3$ as lightly to heavily polluted air quality.

In Figure 5 a disobey phenomena also unveiled in day 24, when monitored daily PM_{10} concentration come to wave crest, the simulated daily PM_{10} trans-boundary contribution ratio drop into low level. This event may be caused by meteorology condition and the change of emission amount, and in day 24 the air pollution is dominated by local emission. Based on the above analysis, it is evident to see that PM_{10} originated from the surrounding provinces has great contributions ratio to PM_{10} concentration in Beijing and played a crucial role in forming PM_{10} pollution in Beijing through long-distance transport.

Table 3. Simulated Monthly ESCRs from Local Industry Emission Source (%)

Industry	ESCR
Stationary emission source	17.43
Fugitive industrial emission source	11.60
Road dust emission source	18.11
Bare land emission source	2.63
Vehicle exhaust emission source	6.90
Construction sites dust emission source	12.45
Resident energy consumption emission source	3.15

4.3. Impacts of Local Industry Emission Sources on Beijing's Air Quality

In the second PSAT setup the research area is divided into 2 regions and local emissions is assigned into 7 industries, such as stationary emission source, fugitive industrial emission source, construction sites dust emission source, road dust emission source, bare land emission source, vehicle exhaust emission source, and resident energy consumption emission source, to better analysis the local industry emission contribution. Table 3 shows the PSAT simulation result of ESCRs from these 7 local industry emission sources on Beijing PM_{10} air quality. The ESCRs were 18.11% from road dust emission source, 17.43% from stationary emission source, 12.45% from

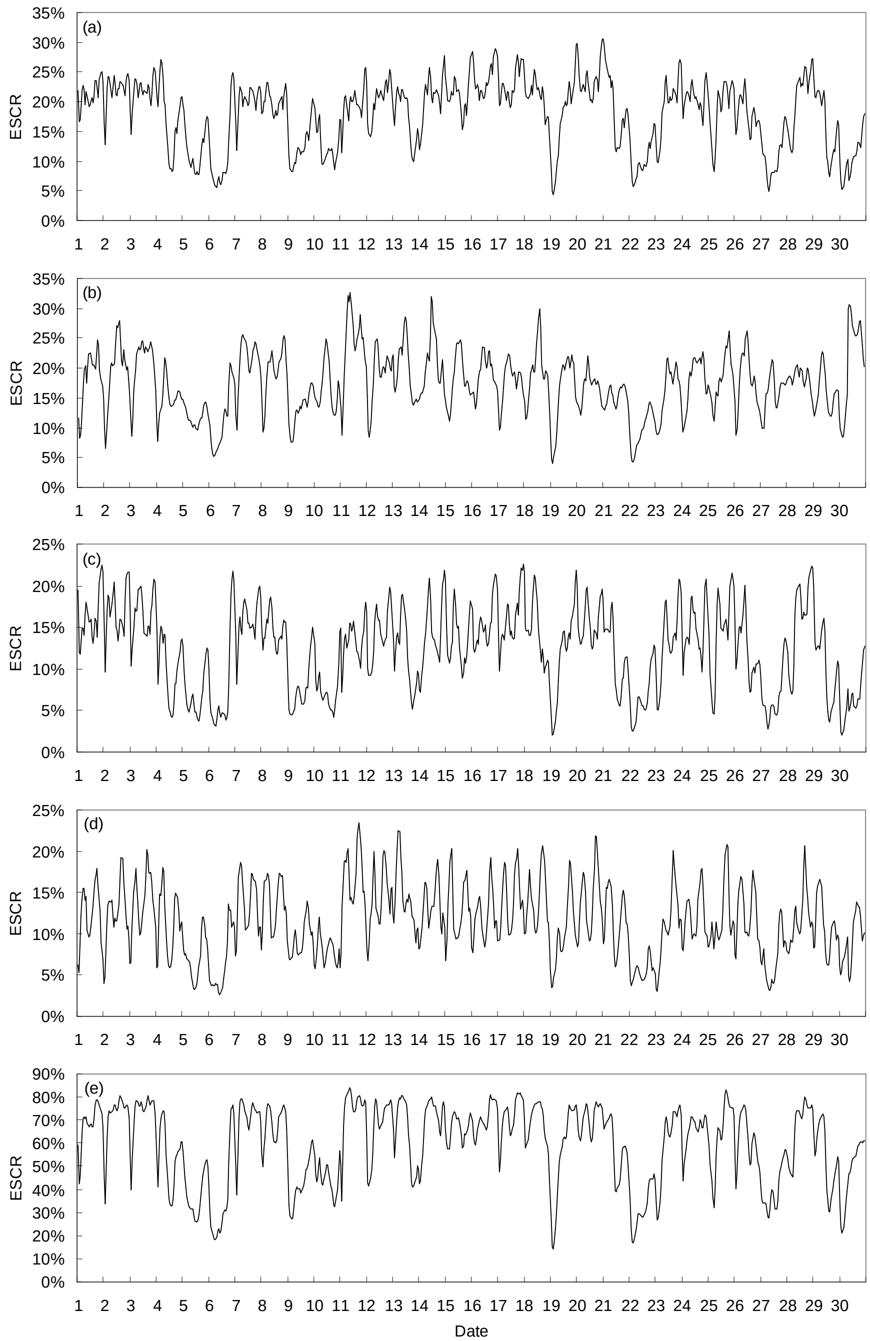

Figure 6. Simulated hourly ESCRs from local four main industries emission source: (a) Road dust emission source, (b) Stationary emission source, (c) Construction sites dust emission source, (d) Fugitive industrial emission source, and (e) Four main industries emission source.

construction sites dust emission source, 11.60% from fugitive industrial emission source, 6.90% from vehicle exhaust emission source, 3.15% from resident energy consumption emission source, and 2.63% from bare land emission source, respectively. The four industries including stationary emission source, road dust emission source, construction sites dust emission source, and fugitive industrial emission source were major contribution sources of local industries emission, which accounted for 59.59% of the Beijing PM_{10} concentration, and 82.45% of PM_{10} concentration from Beijing local emission sources. The contribution of these four main industries would be discussed detailed below.

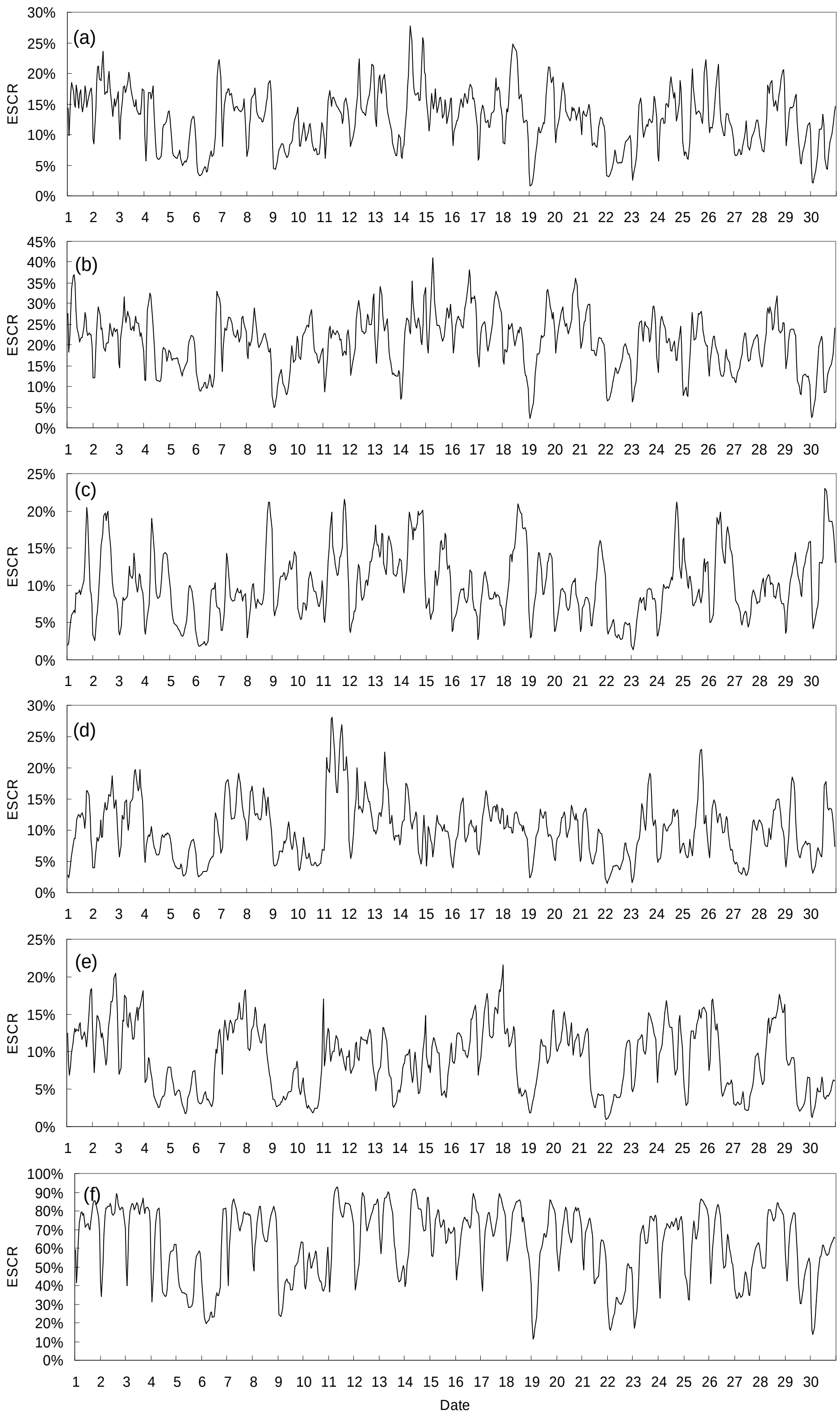

Figure 7. Simulated hourly ESCRs from main regions in Beijing: (a) Urban center of Beijing, (b) Chaoyang, (c) Fengtai, (d) Shijingshan, (e) Haidian, and (f) Urban of Beijing.

The PM_{10} discharge from road dust emission source within Beijing is about 49,000 t/a in 2002, accounting for 28.3% of Beijing's total PM_{10} emissions. According to the PSAT results, the monthly ESCR by the road dust emission source is approximately 18.11%. The hourly ESCR variation is illustrated in Figure 6(a), and the maximum hourly ESCR is 30.57%. The PM_{10} discharge from stationary emission source within Beijing is about 61,000 t/a in 2002, including emissions from industries of construction materials, metallurgy, chemical engineering and processing, power plants, industry boiler, and heating boiler. Such stationary emission discharges account for 35.3 % of the entire emission within Beijing. The monthly ESCR by the stationary emission sources is 17.43%. The hourly ESCR variation is illustrated in Figure 6(b), and the maximum hourly ESCR is 32.56%. The PM_{10} discharge from construction sites dust emission source within Beijing is about 21,000 t/a in the base year, accounting for 12.1% of Beijing's total PM_{10} emissions. The monthly ESCR by the construction sites dust emission source is 12.45%. The hourly ESCR variation is illustrated in Figure 6(c), and the maximum hourly ESCR is 22.59%. The PM_{10} discharge from fugitive industrial emission source within Beijing is about 19,000 t/a in 2002, including fugitive discharges from industries of construction materials, metallurgy, chemical engineering and processing. Such fugitive emission discharges account for 11.0% of the entire emissions within Beijing. The monthly ESCR by the fugitive industrial source is 11.60%. The hourly ESCR variation is illustrated in Figure 6(d), and the maximum hourly ESCR is 23.45%. The PM_{10} discharge from these four main emission sources within Beijing is about 150,000 t/a in the base year, accounting for 86.7% of Beijing's total PM_{10} emissions. According to the PSAT results, the monthly ESCR by these four main emission sources is 59.59%. The hourly ESCR variation is illustrated in Figure 6(e), and the maximum hourly ESCR is 83.79%.

4.4. Impacts of Main Local Emission Sources from Regions in Beijing

For better analysis the geographical emission contributions for these four main industries in Beijing, in third PSAT step the research area was divided into 14 regions and local emissions were assigned into 5 industries, as showed in Table 1. Meanwhile, the PM_{10} ESCRs for Beijing PM_{10} air quality from 13 Beijing regions were calculated in this term of PSAT simulation. The result is showed in Table 4. The area which had big ESCRs were regions of urban Beijing including Chaoyang, urban center of Beijing, Shijingshan, Fengtai, and Haidian, and the ESCRs were 20.60, 12.57, 10.10, 10.03, and 9.05%, respectively. The total PM_{10} ESCRs from urban of Beijing was 62.36%, which accounted for 86.29% of PM_{10} contribution from Beijing local emission sources. The monthly ESCRs from Changping and Shunyi were 2.18 and 2.03%, and other regions were below 2%. Figure 7 shows the PM_{10} hourly ESCRs from urban Beijing, and the maximum PM_{10} ESCRs from Chaoyang, urban center of Beijing (including Dongcheng, Xicheng, Chongwen, and Xuanwu), Shijingshan, Fengtai, Haidian, and urban of Beijing (including Dongcheng, Xicheng, Chongwen, Xuanwu, Chaoyang, Fengtai, Shijingshan, and Haidian) were 41.07, 27.70, 28.06, 23.02, 21.63, and 92.92%, respectively.

Table 4. Simulated Monthly ESCRs from Local Emission Sources (%)

Region	All local emission	4 main local emission	Ratio
Urban center of Beijing	12.57	9.92	78.88
Chaoyang	20.60	17.21	83.55
Fengtai	10.03	8.40	83.72
Shijingshan	10.10	8.84	87.55
Haidian	9.05	7.30	80.62
Mentougou	1.74	1.51	86.80
Fangshan	1.72	1.42	82.54
Tongzhou	0.87	0.63	72.38
Shunyi	2.03	1.58	77.69
Changping	2.18	1.76	80.63
Daxing	0.55	0.40	72.76
Huairou and Yanqing	0.49	0.38	77.34
Pinggu and Miyun	0.34	0.26	75.58
All Beijing city	72.27	59.59	82.46

Figure 8 showed the ESCRs of four main industries from 13 different regions in Beijing. The main contribution regions for stationary emission source were Chaoyang, Fengtai, Shijingshan, urban center of Beijing, Haidian, and Mentougou, and the ESCRs were 4.67, 4.16, 3.12, 1.54, 1.02 and 1.00%, respectively. The main contribution regions for fugitive industrial emission source were Chaoyang, Shijingshan, and Fengtai, and the ESCRs were 4.67, 3.95, and 1.55%, respectively. The main contribution regions for road dust emission source were Chaoyang, urban center of Beijing, Haidian, Fengtai, Shijingshan, and the ESCRs were 5.08, 4.41, 2.89, 1.66, and 1.28%, respectively. The main contribution regions for construction sites dust emission source were urban center of Beijing, Haidian, Chaoyang, and Fengtai, and the ESCRs were 3.98, 2.96, 2.79, and 1.02%, respectively. Adding up the ESCRs of these four main industries according to the regional category, we get the total ESCRs for 13 regions in Beijing, and the result is showed in Table 4 and Figure 8. The main contribution regions for these four main industries were Chaoyang, urban center of Beijing, Shijingshan, Fengtai, and Haidian, and the ESCRs were 17.21, 9.92, 8.84, 8.40, and 7.30%, which accounted for 83.55, 78.88, 87.55, 83.72, and 80.62% for all emission source contribution in these regions. The ESCR of these four main industries from urban Beijing is 51.67%, which accounted for 82.86% of PM_{10} concentration from all emission sources in urban Beijing, accounted for 86.71% of PM_{10} concentration from four main industries in Beijing, and accounted for 71.50% of PM_{10} concentration from all industry emission in Beijing. Therefore, we believe that stationary emission sources, fugitive industrial emission source, construction sites dust emission source, and road dust emission source located in the urban area of Beijing were the main emission source from Beijing, which had great influence on PM_{10} air quality in Beijing.

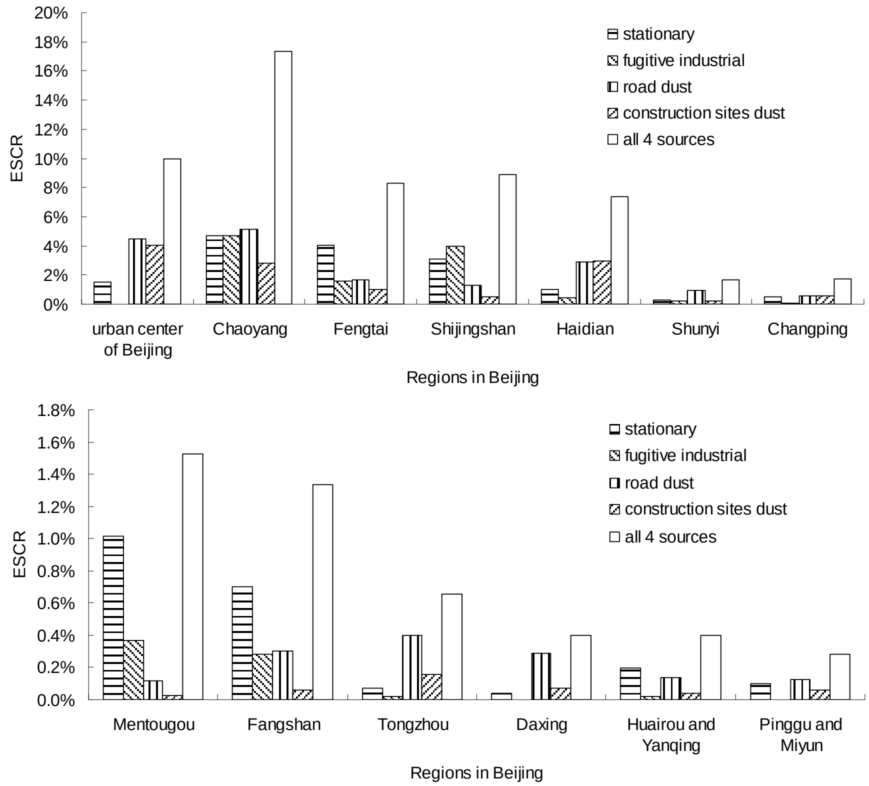

Figure 8. Simulated monthly ESCRs for four main industries emission source from 13 regions in Beijing.

Figure 9 shows the four main industries PM_{10} hourly ESCRs from Chaoyang, urban center of Beijing, Shijingshan, Fengtai, Haidian and urban of Beijing, and the maximum hourly ESCRs were 35.15, 21.77, 25.29, 18.95, 18.24, and 80.17%, respectively.

4.5. Discussion

Based on above analysis, it could be find out that the four main industries emission source from urban Beijing (stationary emission source, road dust emission source, construction sites dust emission source, and fugitive industrial emission source) were the main emission sources contributing to the PM_{10} value in local Beijing, which accounted for 71.50% ESCR for all industries emission in Beijing. Therefore, much efforts should be paid firstly in urban Beijing to control and reduce PM_{10} emission from stationary emission source, fugitive industrial emission source, construction sites dust emission source, and road dust emission source, including implementing high-efficiency dust removal, gradually converting the scattered coal-fired boiler to clean-energy boilers, implementing stricter PM emission standards and control method, closing or moving large industrial enterprises, strengthening road pavement and vehicle washing, improving machinery sweeping and washing of the roads. Besides, PM_{10} trans-boundary transportation played a crucial role in forming of PM_{10} pollution in Beijing. So much effort should also be placed on demanding more pollution reduction from surrounding provinces when Beijing takes positive steps to reduce its own pollution emissions.

PSAT is a high efficient and flexibility technique to depict the relationship between emission and air quality contribution. In this study, we use this technique established a research method to step by step illustrate PM_{10} source apportionment in Beijing city in November 2002, interpret the main PM_{10} contributor outside of Beijing, focuses on main industries and regions in Beijing, and find out main contribution sources in Beijing. The result can provide basic knowledge to set up optimization emission control and reduction plan for Beijing city. Using this technique we can deeply understand emission and concentration contribution relationship in Beijing for different season or different month. Then, we can identify the PM_{10} characteristics in different time, and establish corresponding plan to control PM_{10} pollution in different month or season.

Comparing with zero-out method, PSAT technique can perfectly simulate nonlinear chemical reaction in atmosphere, and eliminate the interference of system error. Besides, PSAT technique can improve simulation and analysis speed. Comparing with other source apportionment technique (e.g. chemical mass balance (CMB), principal factor analysis (PFA), and positive matrix factorization (PMF)), PSAT technique can comprehensively analyze chemical, physical, and meteorological process in atmosphere, and provide high spatial and high temporal result about relationship between emission source and air quality contribution.

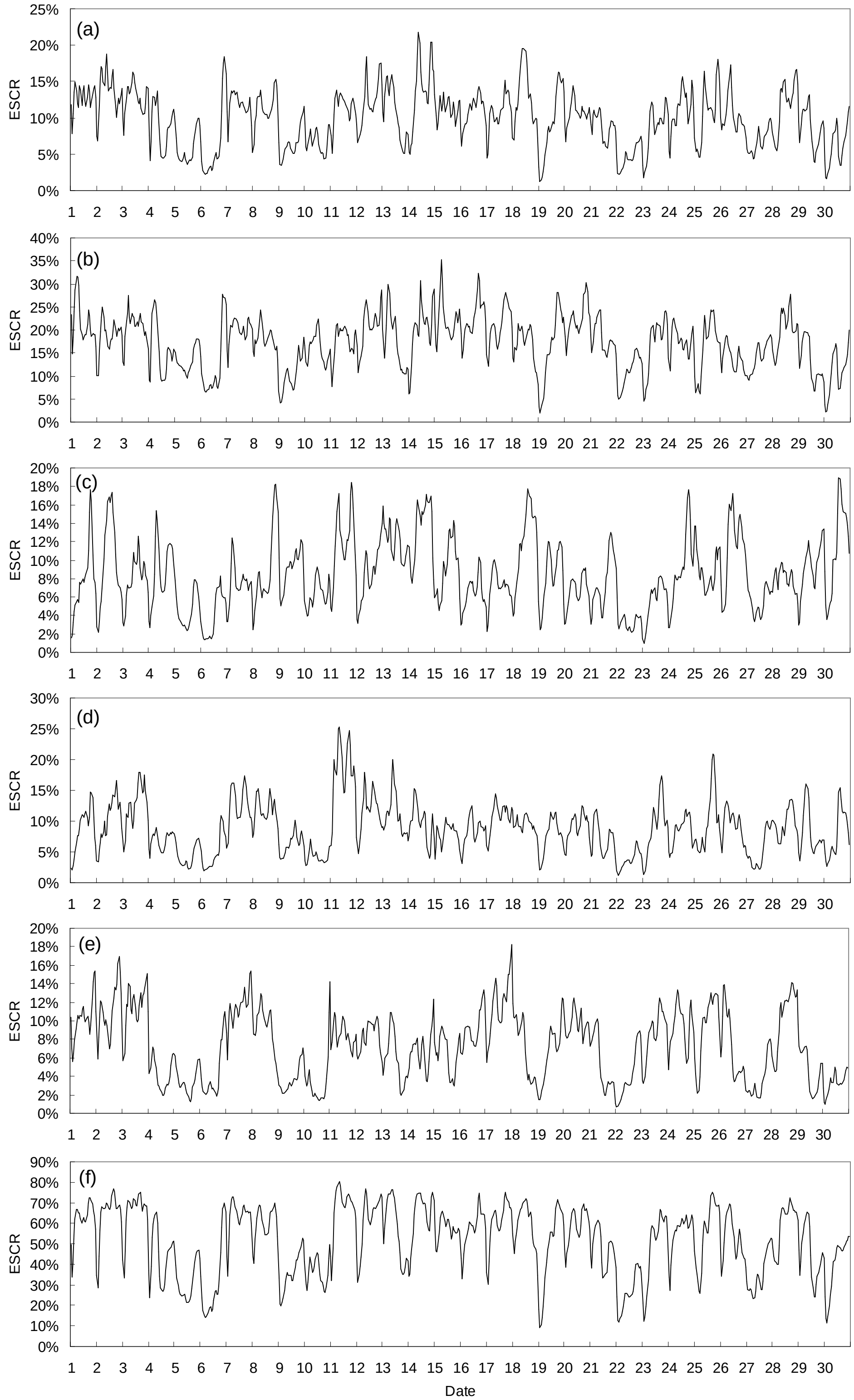

Figure 9. Simulated hourly ESCRs for four main industries emission source from main regions of Beijing: (a) Urban center of Beijing, (b) Chaoyang, (c) Fengtai, (d) Shijingshan, (e) Haidian, and (f) Urban of Beijing.

Through using PSAT technique, the main PM_{10} contribution from multiple regions and industries can be identified, which had high contribution ratio in study area. In further study, we can perform sensitive study of these main contribution regions and industries to find which source had high sensitive reaction, which means when adding or removing same amount of emission, the sources which have high contribution concentration changes. Combining these result with atmospheric assimilative capacity (AAC) and economical technology study results, more cost-effective plan for regional air quality management can be identified (Cheng et al., 2007a).

5. Conclusions

In this study, a coupled MM5-CAMx air quality modeling system is proposed for simulating the PM_{10} concentration in Beijing. The particulate matter source apportionment technology (PSAT) was introduced into the developed modeling system to investigate PM_{10} source apportionment from multiple regions nearby Beijing, local industries emission sources in Beijing, and main local industries emission sources from different regions in Beijing. This method can effectively identify PM_{10} pollution problem in a metropolis region and provide a scientific basis for air pollution control and mitigation.

The result indicated that the effect from regions nearby Beijing could not be ignored, which was one of the main factors of PM_{10} air pollution in Beijing. The surrounding region including Hebei, Shanxi, Tianjin, and Inner Mongolia, with an ESCR of 26.65%, was a big PM_{10} contributor outside of Beijing. Stationary emission source, fugitive industrial emission source, construction sites dust emission source, and road dust emission source were four important local emission source in Beijing, which had a 59.59% ESCR. Further analysis showed that these four industries emission sources from urban Beijing were main contributor of Beijing PM_{10} air quality, with an ESCR of 51.67%, which accounted for 82.86% of PM_{10} concentration from all emission source in urban Beijing, accounted for 86.71% of PM_{10} concentration from four main industries in Beijing, and accounted for 71.50% of PM_{10} concentration from all industry emission in Beijing. The results demonstrate that, in order to keep the Beijing air quality at a safe level, PM_{10} emissions from the four industries in the urban as well as those from surrounding areas nearby Beijing have to be mitigated simultaneity. This is useful for supporting to establish a cost-effective plan for the city's air quality management.

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